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LARGE NAVIGATIONAL BUOY ENGINE-GENERATOR TEST PROGRAM. PART I. TECHNICAL DISCUSSION AND CONCLUSIONS

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FINAL REPORT

LARGE NAVIGATIONAL BUOY ENGINE-GENERATOR TEST PROGRAM

PART 1

TECHNICAL DISCUSSION AND CONCLUSIONS

Submitted to

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400 Seventh Street
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13. ABSTRACT

Report presents background information and a summary of tests conducted during the period 1 September 1969 to 13 July 1972. The testing was performed at the General Dynamics Facilities in San Diego, California. Included is a description of the engine-generator units, and modifications performed on these units to adapt them to the LNB mission. The test programs shows that the diesel engine-generator system for the LNB exceeds the performance objectives originally established for the system. GenSet No. 1 operated continuously for 9000 hours without attention and 24,557 hours without overhaul. GenSet No. 2 completed 1079 separate starting sequences including cold starts down to 9°F.

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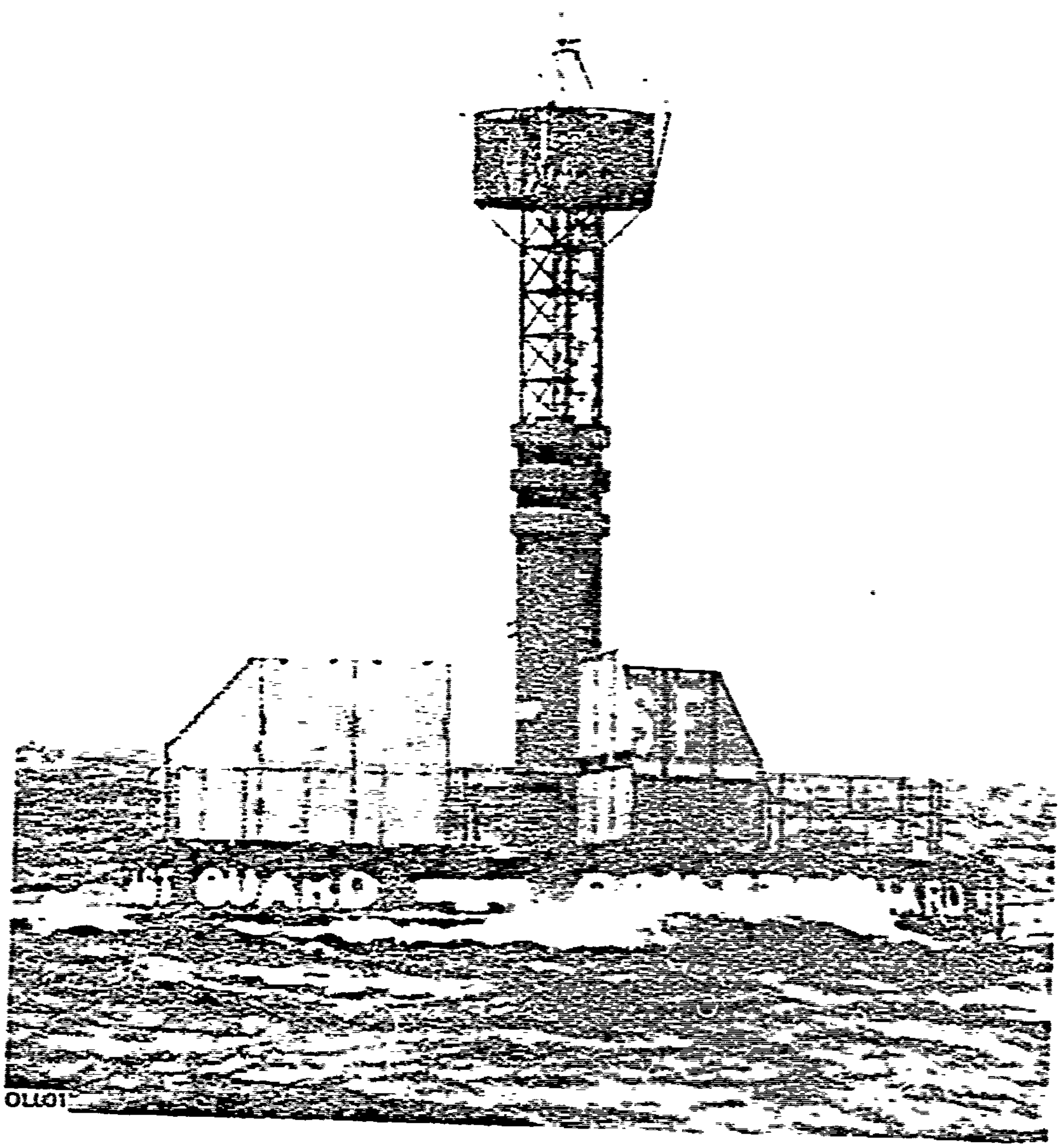
SUMMARY

This document is the final report on the Large Navigational Buoy (LNB) Engine-Generator Test Program, and is submitted in accordance with Amendments 5 and 12 of Contract DOT-CG-91.904A. These amendments covered the continuation of endurance testing of one diesel engine generator, and cyclic/start tests of a second diesel engine generator (an interim report on the program was submitted in October of 1971). The test program as reported is an extension of company-sponsored research and evaluation of diesel engine generators for Ocean Data Stations and Large Navigational Buoys, a project that was initiated in 1966. This company-sponsored effort was part of a continuing program to advance the technologies that are fundamental to reliable, long-term, unattended operation of automatic ocean navigation stations. As a result of the favorable development progress with the power plant development program, as reported earlier, the U.S. Coast Guard provided funding support for continued evaluation of the LNB power plant configuration.

This report presents background information and a summary of the tests conducted during the period 1 September 1969 to 13 July 1972. The testing was performed at General Dynamics facilities in San Diego, California. Included herein is a description of the engine-generator units, and modifications performed on these units to adapt them to the LNB mission. The report also includes information obtained following disassembly and inspection of Engine Generator No. 2 (cyclic and starting tests) in January of 1972, and similar information obtained following the disassembly and inspection of Engine Generator No. 1 (endurance test) in July of 1972.

The evaluation program as reported here, and the operations of the power plants in the Large Navigational Buoys now deployed along the Atlantic, Pacific, and Gulf Coasts, have shown that the diesel engine-generator system for the LNB application meets and indeed exceeds the performance objectives originally established for the system. Engine Generator No. 1, for example, operated continuously for 9000 hours without attention, and for 24,557 hours without overhaul under test loads more severe than actual operational conditions. Engine Generator No. 2 satisfactorily completed all cyclic tests, including cold start tests down to 9°F, and 1079 separate starting sequences.

The summary conclusion drawn from the test program is that the diesel engine-generator unit is satisfactory for all operational requirements of the LNB in its present configuration, and is very probably capable of operating at significantly higher average loads should future mission requirements call for additional power.



Frontispiece — Diesel Powered Large Navigational Buoy

1. INTRODUCTION

Early in 1960, the Ocean System Programs group of General Dynamics initiated studies to develop a power system capable of long-term unattended operation for use on Ocean Data Station buoys. The size and nature of the electrical loads and the availability of off-the-shelf hardware led to the early selection of a propane-fueled engine-generator system that maintained the state of charge on a heavy-duty storage battery.

In 1966, under contract to the U.S. Coast Guard, General Dynamics adapted the propane fueled system for use on the prototype Large Navigational Buoy (LNB), a buoy designed for lightship replacement. The in-service evaluation of this power system indicated that the use of propane fuel posed some special problems for the Coast Guard. Further, indications at that time pointed to increased power requirements for future navigational buoy systems. With this situation apparent, General Dynamics reviewed its prior experience with various engine types, and then initiated a specific effort to investigate all available diesel engine generators in the power range of 2 to 10 kW, which might meet the operational LNB requirement. The investigation included testing of two engine-generator units prior to their selection for the production LNB. The tests, which began early in 1969, led eventually to the test program reported here.

The initial phase of the diesel power plant investigation was completed in 1967, and identified more than 70 potential candidate engine generators in the power range under 7.5 kilowatts. The list included water- and air-cooled engines, and single- and two-cylinder versions of both foreign and domestic manufacture. At this point, candidate engines were appraised and the list reduced to those which were judged as most likely to produce the desired performance, using the following criteria:

a. Reliability based on documented performance tests, field experience, design features (air versus water cooled, etc.) and warranty.

b. Maintainability considerations including weight and volume, rated time before overhaul, general availability of repair parts, accessibility for repairs, and adaptability to existing USCG maintenance facilities and personnel training programs.

c. Other considerations such as cost, fuel consumption, suitability for operation in the marine environment, and growth potential.

For example, it was felt that liquid-cooled engine units would tend to be less reliable for the buoy application than would air-cooled versions, because liquid-cooled units require plumbing installations that are inherently susceptible to leaks and corrosion. Similarly, with respect to maintainability, the liquid-cooled units were generally found

to be heavier than air-cooled engines of equivalent horsepower and thus less desirable in view of the requirement for changing an engine at sea. Considerations such as these were evaluated with the more basic qualities of the units (such as the demonstrated operational record of the candidate engine-generator combinations) in deciding upon the recommended arrangement. Thus, with long-term unattended reliability as the principal decision-making factor, and with operating hours before maintenance as the second factor of evaluation, followed by other considerations: the selection of an engine generator for the LNB was made. The unit selected (which most closely met the aforementioned criteria) was a modified Lister SR-1 single-cylinder, 6-hp, 1800-rpm, air-cooled diesel coupled to a Lima 120-volt, 60-Hz, single-phase, brushless, drip-proof generator of 3.5 kW output. The unit was mounted on a vibration-isolation base, and (as modified) was warranted to operate for 6000 hours without any maintenance or attention, and for 17,000 hours before major overhaul.

As mentioned earlier, two of these engine generators were set up in 1969 under test conditions designed to exceed those which the units would experience during normal operation in a Large Navigational Buoy configuration. The primary objective of the test program was to establish the overall suitability of the units for operation in the LNB. The secondary objective was to gain information on potential failure modes which could affect recommended preventive maintenance procedures for the operators of such buoys. Specifically, the primary test objectives were:

a. To establish the ability of the units to operate under simulated buoy loads in excess of 6000 hours continuously, without attention

b. To establish the ability of the units to operate under simulated buoy loads for 17,000 hours without major overhaul

c. To verify all design modifications performed on the basic units to adapt them to the LNB mission

The secondary test objectives were:

a. To establish preventive maintenance procedures for ancillary components such as injectors, pumps, etc.

b. To determine the probable maximum engine life before overhaul under buoy system loads

c. To determine the effects of cold starting and exercise (on/off sequences) on the engine and its components

With these objectives in mind, the test program covered by this report was initiated, and has now been successfully completed.

The program was divided into five discrete parts:

a. Endurance testing under steady load

b. Endurance testing under cycling loads

c. Cold start tests

d. Exercise tests

e. Accelerated starting/exercise tests

The following sections of Part 1 of this report provide first a summary description of the Large Navigational Buoy power system now in use, followed by technical discussions of the test program and the results obtained. For convenience, the accumulated test data (log sheets from the tests themselves) are bound separately in Part 2 of the report.

2. LARGE NAVIGATIONAL BUOY POWER SYSTEM

The Large Navigational Buoy (LNB) power system consists of two sets of diesel engine generators, a controller, batteries, fuel tanks, filters, and exhaust ducting. In normal operation the engine generators (installed in two separate buoy compartments as shown in Figure 2-1) are programmed to operate as primary and secondary sources of power. The secondary (standby) unit is inoperative until called into service. Figure 2-2 shows the diesel engine generators installed in the buoy compartments, and Figure 2-3 is a photograph of one of the units in an LNB.

The engine generators operate, when on-line, at average loads of approximately 1000 watts, as compared to their rated output of 3.5 k[illegible]put voltage is 120 Vac within ±10%; frequency is maintained at 60 Hz ±5%. See Figure 2-4 for the power generation system block diagram, and Figure 2-5 for a typical load diagram.

The controller monitors the voltage and frequency output of the operating engine, shuts it down and starts the secondary engine if limits are exceeded, programs the periodic exercise start-up of the secondary engine, and indicates performance and status of the power-generating system to the Remote Control and Monitoring System (RCMS). The controller assembly is divided into two parts: the monitoring section and the transfer section. The monitoring section contains voltage and frequency sensors, time delay relays, timers, and monitor contacts for both automatic (normal operation) and exercise modes. The transfer section contains switches of the two-coil double-break contact type, mechanically and electrically interlocked to provide double protection against out-of-sequence or simultaneous closing. The controller is in the automatic operating mode at all times except when commanded or timed into the exercise mode. The voltage and frequency sensors continually monitor the primary engine-generator output. Any deviation from the specification for a period greater than 5 seconds will disconnect the primary engine generator from the bus, and initiate the standby engine starting cycle. The standby engine-generator output then is monitored by the voltage and frequency sensors to verify that the output is within specification. After a delay to allow the engine to warm up without load, the output of the standby engine-generator is connected to the bus and the bus is changed from primary to standby, and the contacts that indicate a primary engine generator stoppage are closed. Engine hour meters are shut down or energized to correspond with the change of operating engine. From that point on, the output of the standby engine generator is continuously monitored by its voltage and frequency sensors to assure that it remains within specification. Any deviation for a period greater than 5 seconds will disconnect the standby engine generator from the bus, shut down the engine, and close the Remote Control and Monitoring System contacts that indicate a standby engine-generator stoppage to the shore control station. The power generation system remains in this condition until reset.

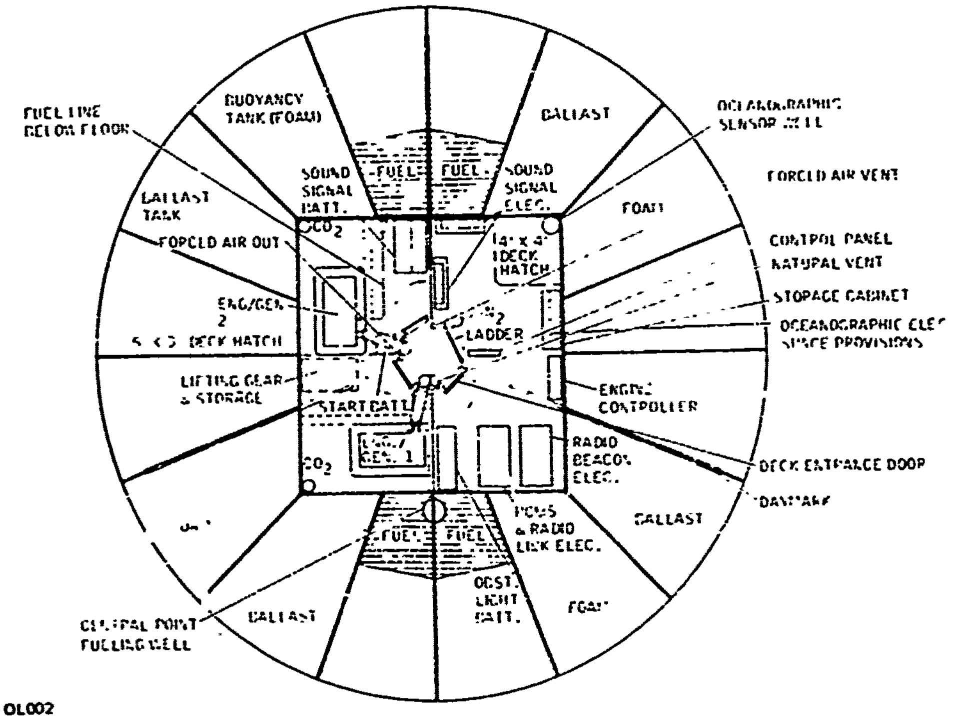


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Figure 2-1. Typical LNB Hull Division and Compartment Arrangement

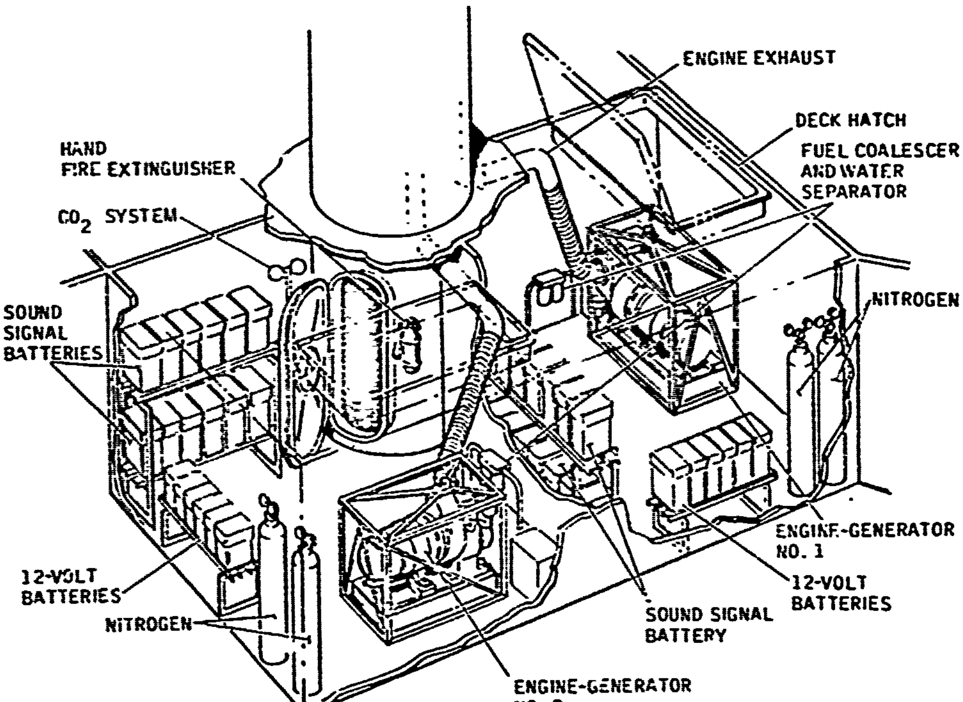

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Figure 2-2. Typical LNB Engine-Generator Installation

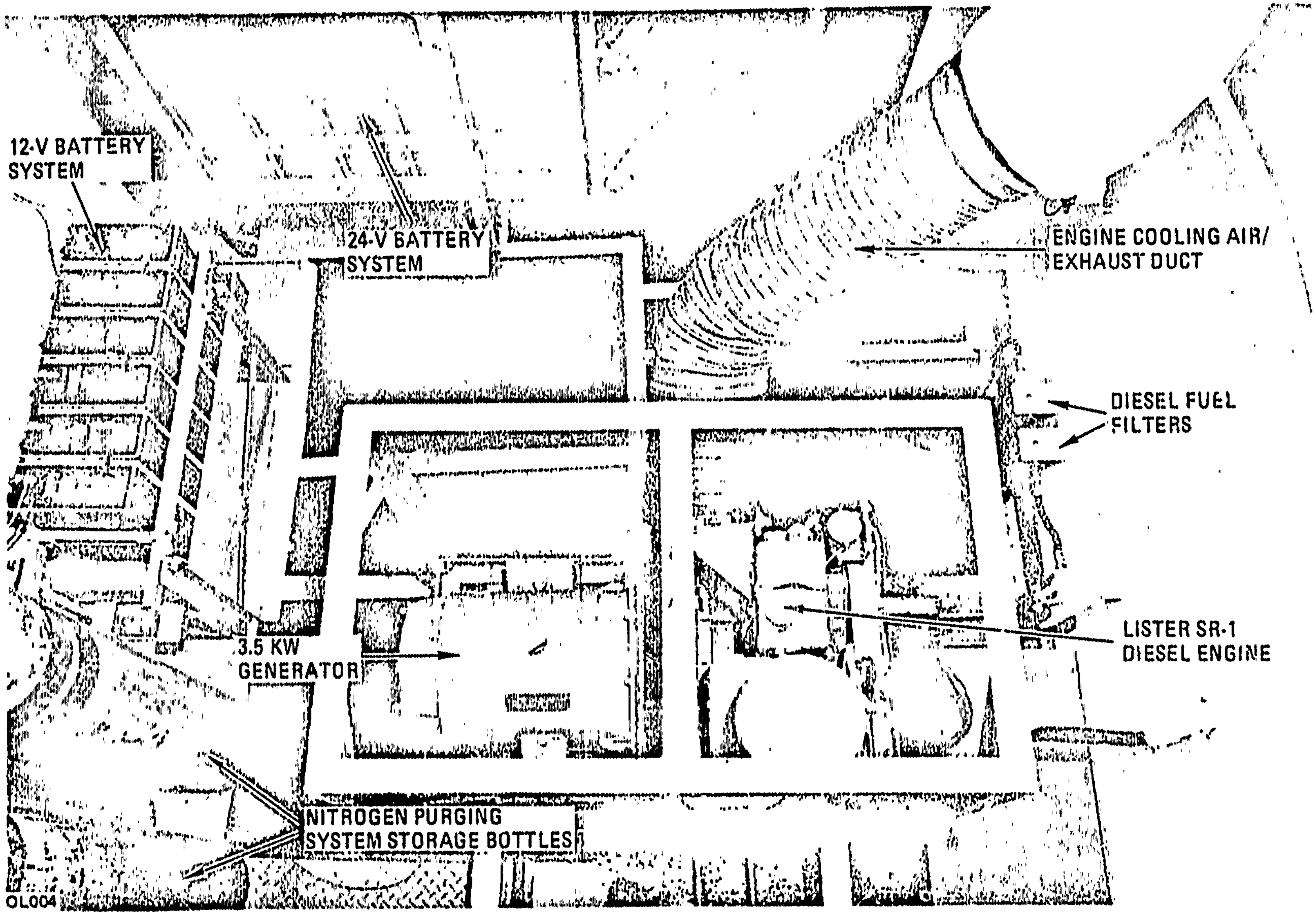

Figure 2-3. Engine Generator in Buoy Compartment (looking down)

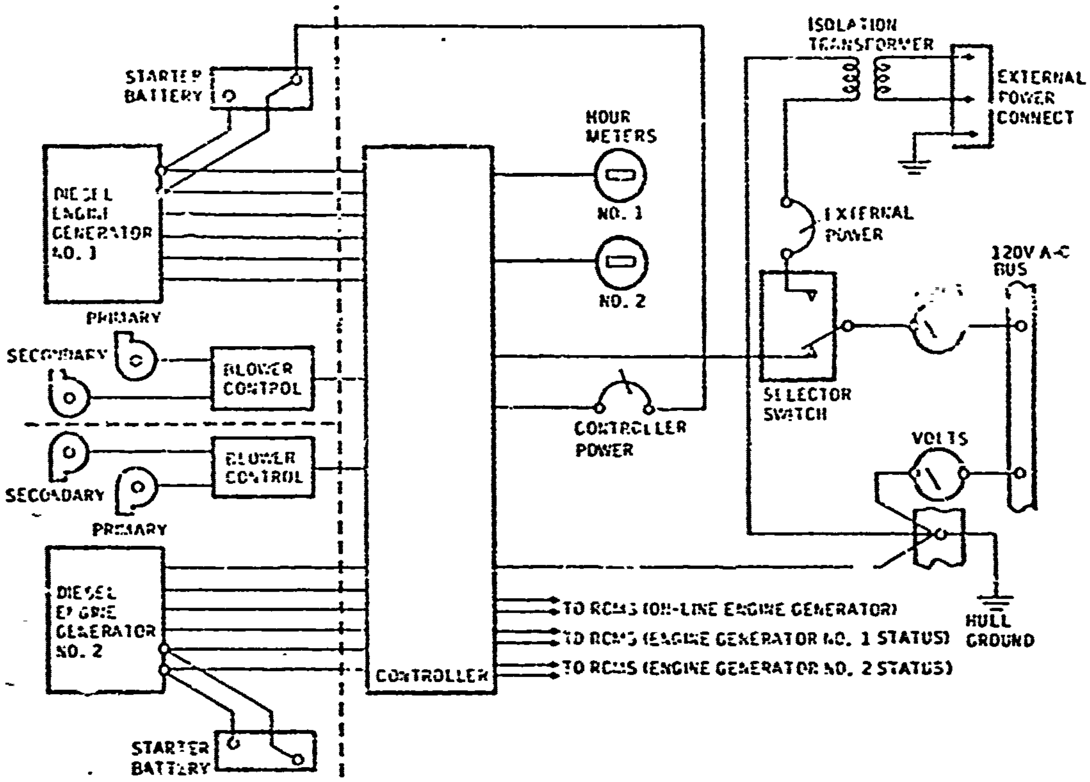

Figure 2-4. LNB Power System Block Diagram

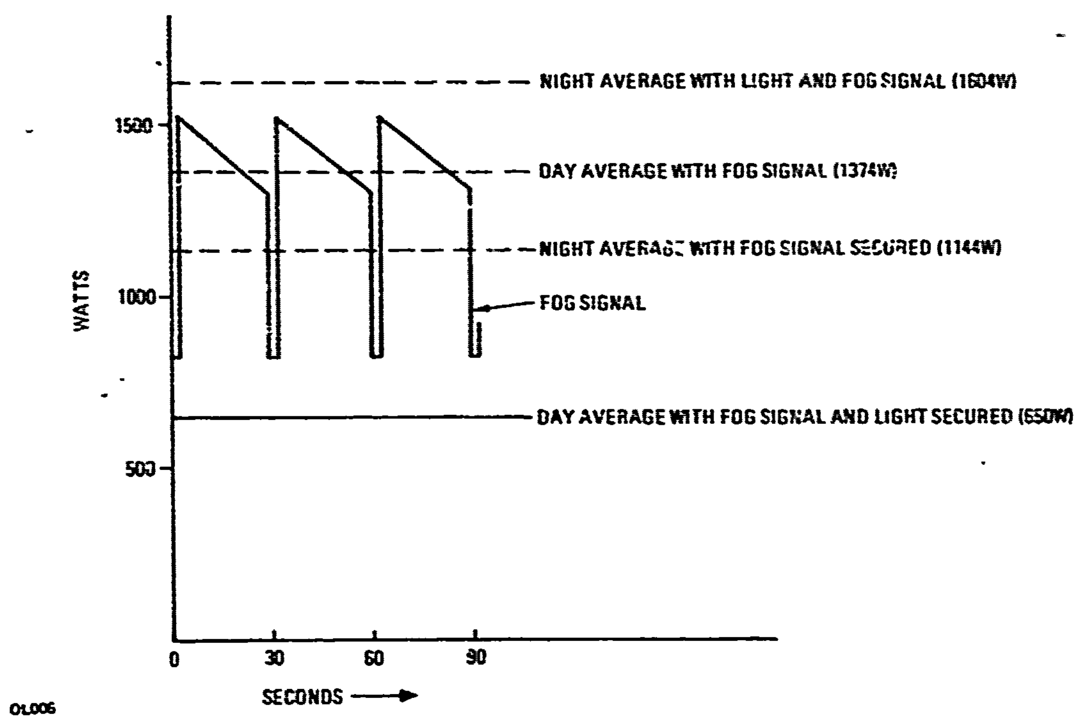

Figure 2-5. Typical LNB Electrical Load

3. TEST SYSTEM DESCRIPTION

3.1 TEST INSTALLATIONS

Except for the cold start tests, all testing was conducted within the room illustrated in Figure 3-1 at the General Dynamics facility located at Lindbergh Field in San Diego, California. Figure 3-2 is a view of the two test equipment cabinets utilized, and Figure 3-3 is a close-up view of Engine Generator No. 1 undergoing endurance testing. The similarity of the installation shown in Figure 3-3 to that shown in Figure 2-3 of an actual buoy installation is readily apparent.

The test room is of reinforced concrete construction, is approximately 22-ft long by 15-ft wide, and has a ceiling height of approximately 12 ft. Major access is provided via a large roll-up type door located at one end. The engines in the room were provided with inlet and exhaust ducts to simulate the length and diameter of the buoy induction/exhaust system.

The cold start testing was performed in a large refrigerated truck (Figure 3-4). For this test, the engine generator, lube oil reservoir, and fuel tank were mounted in the refrigerated portion of the truck for a 6-week period. Several cooling cycles were initiated prior to the start of the tests to establish the rate of cooling obtainable from the truck's refrigeration machine. The refrigeration unit was operated either electrically or by gasoline engine. The power and sensor cables were extended from the truck-mounted components to the test room where the control and test equipment was located.

3.2 ENGINE GENERATOR DESCRIPTION

Both engine generators used in the test were modified and adapted to General Dynamics Specification 25-00202. The characteristics of the units tested were as follows:

Engine:	Modified Lister
Model:	SR-1
No. of Cylinders:	1
Horsepower:	6
RPM	1800
Fuel Type:	No. 2 diesel
Crankcase Type:	Dry sump (separate oil reservoir)

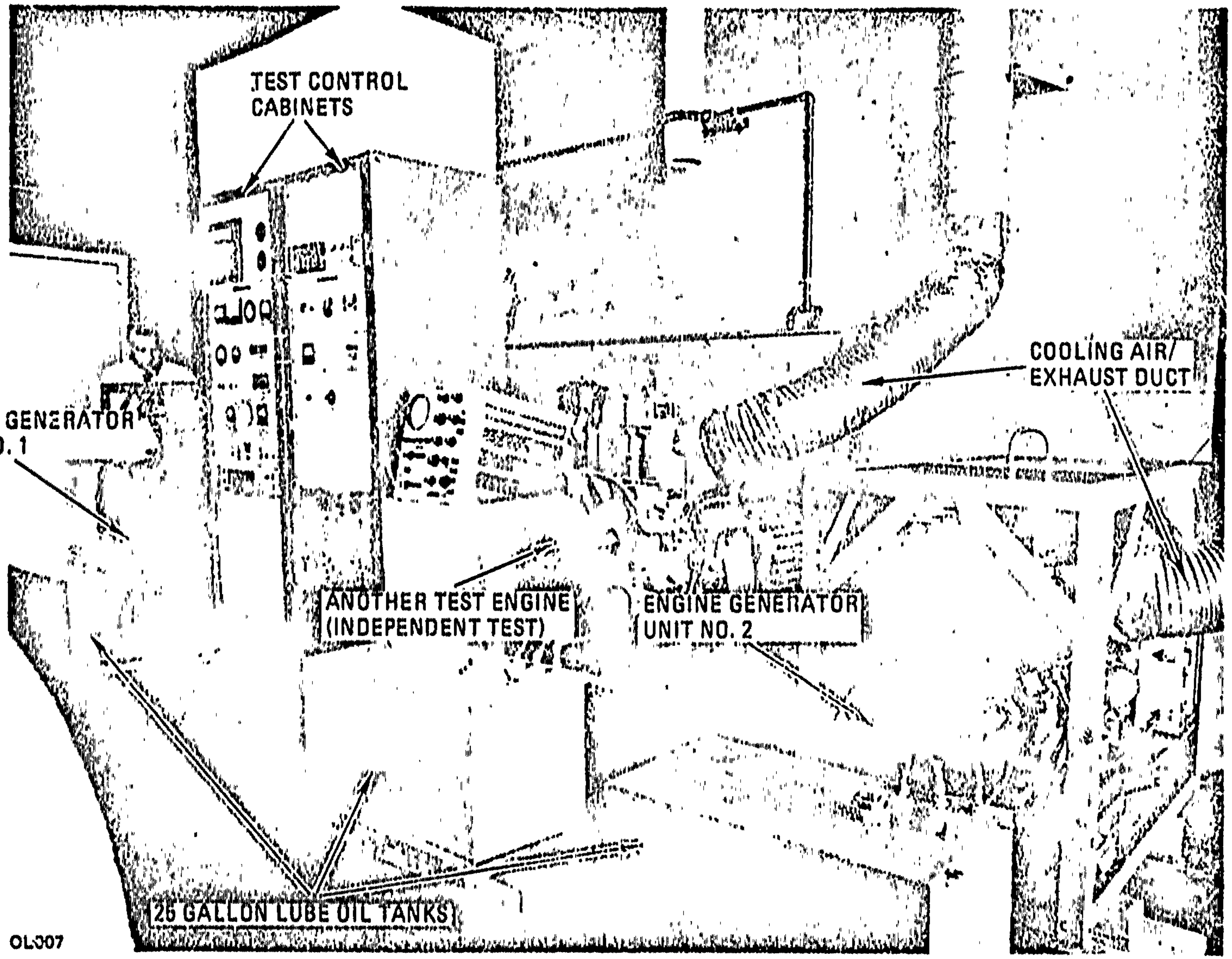

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Figure 3-1. View of Test System

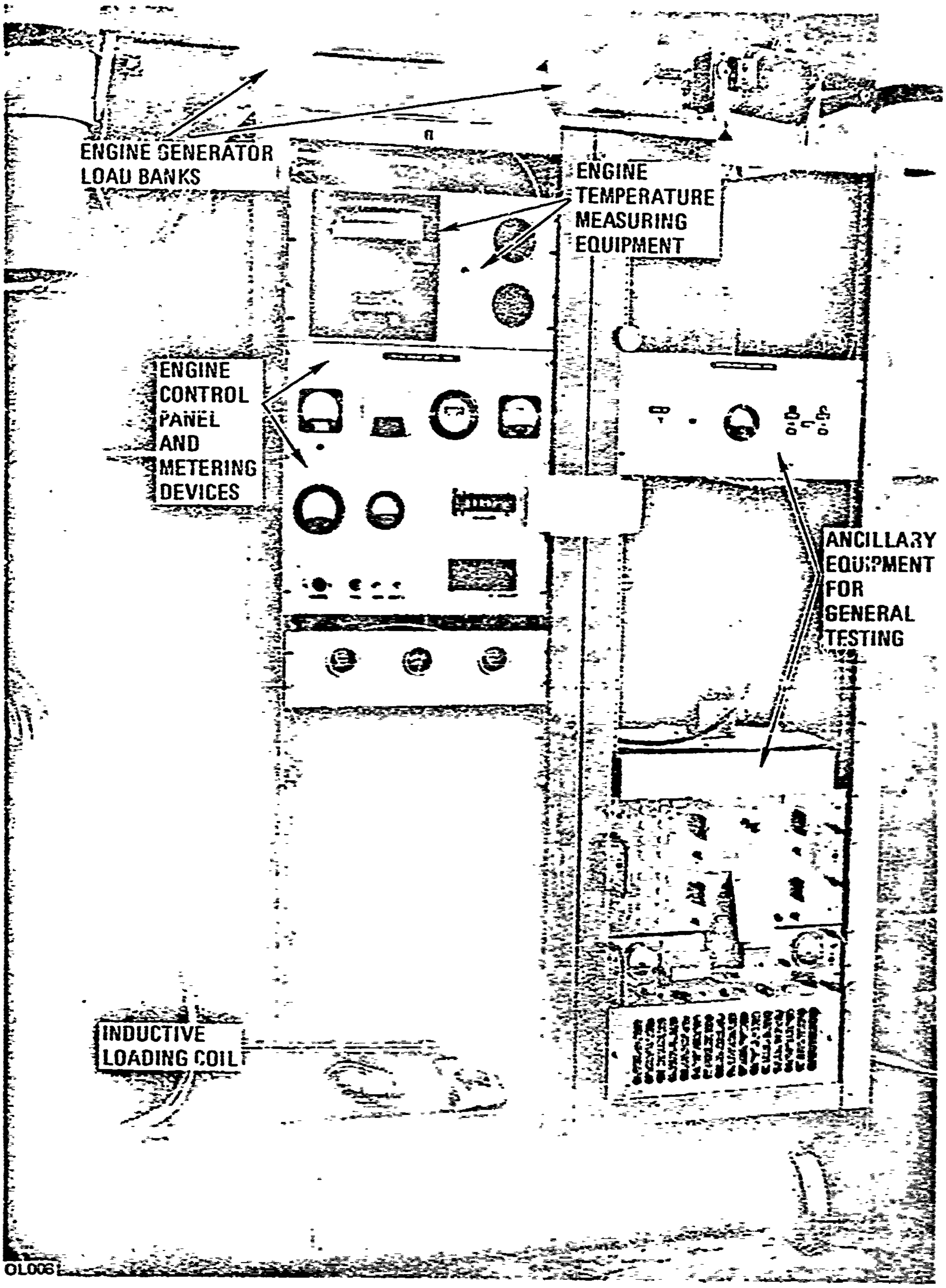

Figure 3-2. Test Control Cabinets

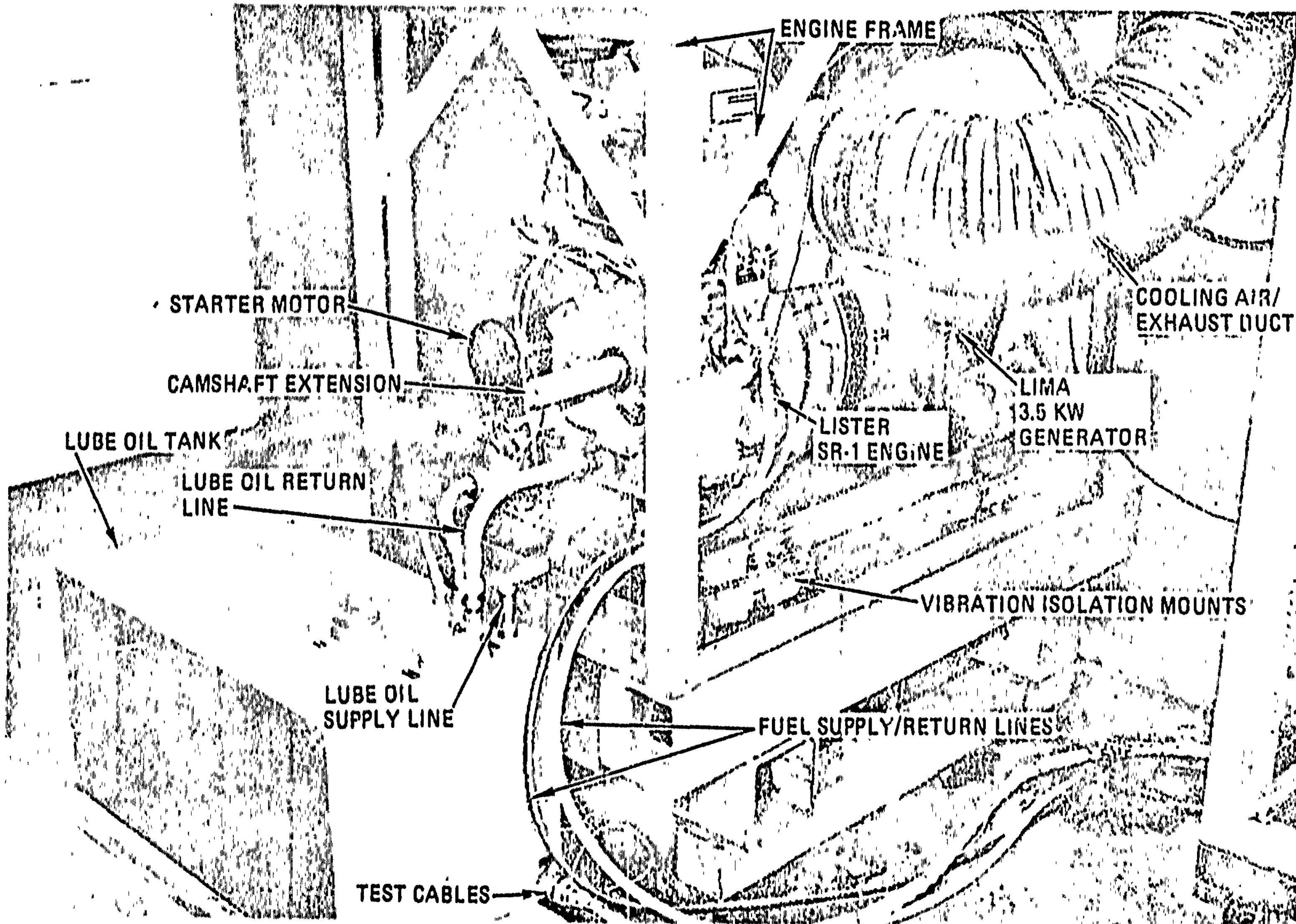

Figure 3-3. Engine Generator No. 1 Undergoing Test

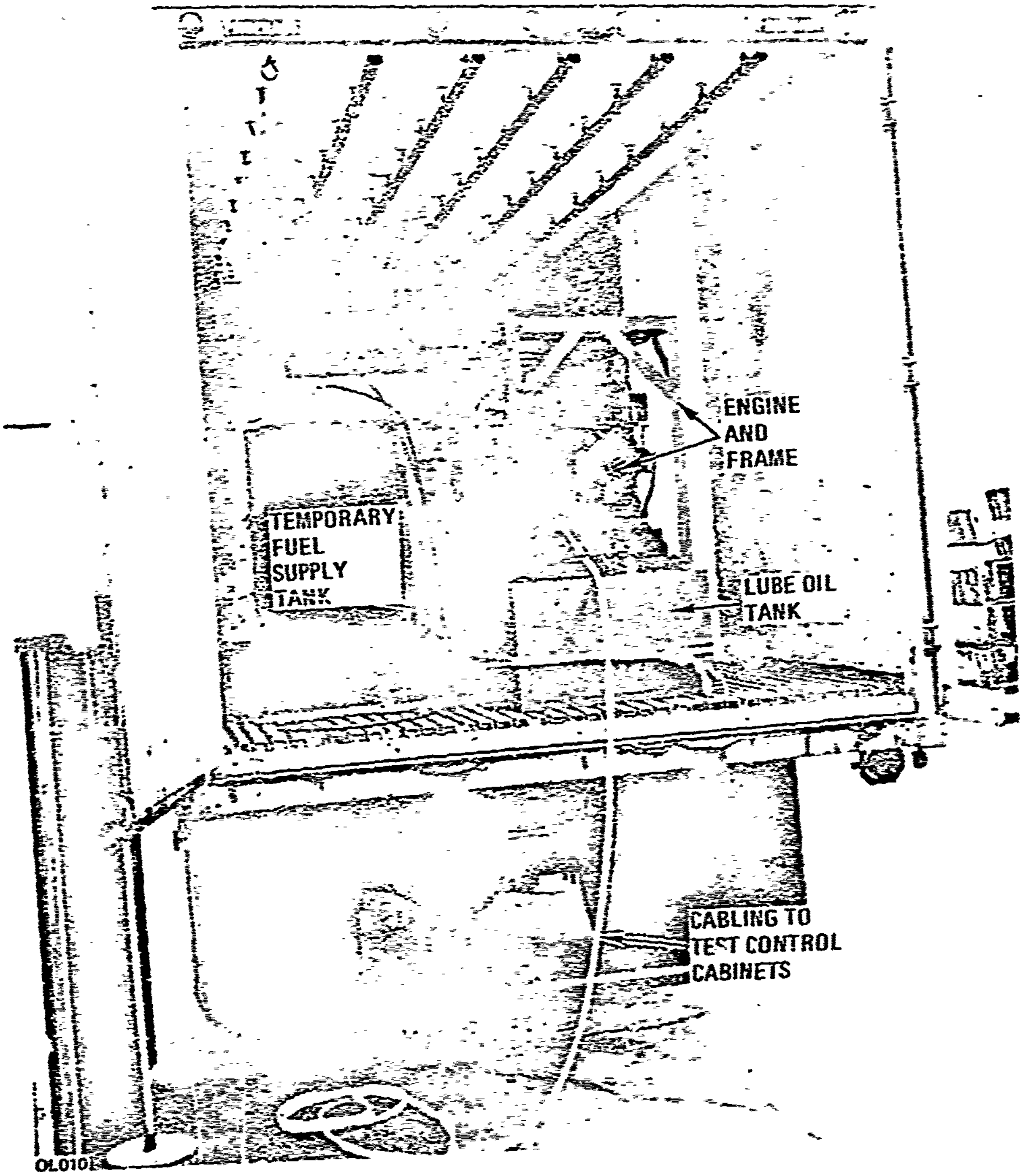

Figure 3-4. Cold Start Test Installation

Cooling:	Forced air (integral engine-driven fan)
Generator:	Lima Electric
Model:	MACR (single-bearing, drip-proof type)
Volts:	120/240
Phase:	Single
KW:	3.5
Package Weight:*	875 lbs
Package Length:*	43 in.
Package Width:*	26 in.
Package Height:*	36 in.
Mounting Base:	Fra-Bol Vibration Isolating (Bolstad Company)

*Excluding separately mounted lube oil reservoir.

3.3 FUEL SYSTEM DESCRIPTION

The fuel system consisted of a replica of one LNB tank section (1200-gallon capacity), fuel filters, lines, and a nitrogen pressure system. The tank was built to the buoy hull design with an epoxy type interior finish identical to the buoy tankage. Figure 3-5 illustrates the dry nitrogen purging system installed to exclude air and water vapor from the fuel tank. Two stages of fuel filtration were provided. The first filter and water coalescer was a dual Fram unit installed in the fuel line next to the fuel tank. The second filter was mounted on the diesel engine unit. Each test engine generator was provided with a fuel supply line and fuel return line as in the LNB. An externally-mounted, engine-driven, diaphragm-type pump supplied fuel from the supply line to the engine fuel injection pump.

3.4 LUBRICATING SYSTEM DESCRIPTION

The engine was modified to a dry-sump type crankcase configuration, and was connected to a separately-mounted 25-gallon lube oil reservoir by three lines. One line was the oil suction line leading from the reservoir to the engine-driven pump inside the crankcase. The second line was a return line which scavenged oil from the crankcase, and drained into the lube oil reservoir by gravity flow. The third line was an equalizing vent between the lube oil reservoir and the upper engine crankcase.

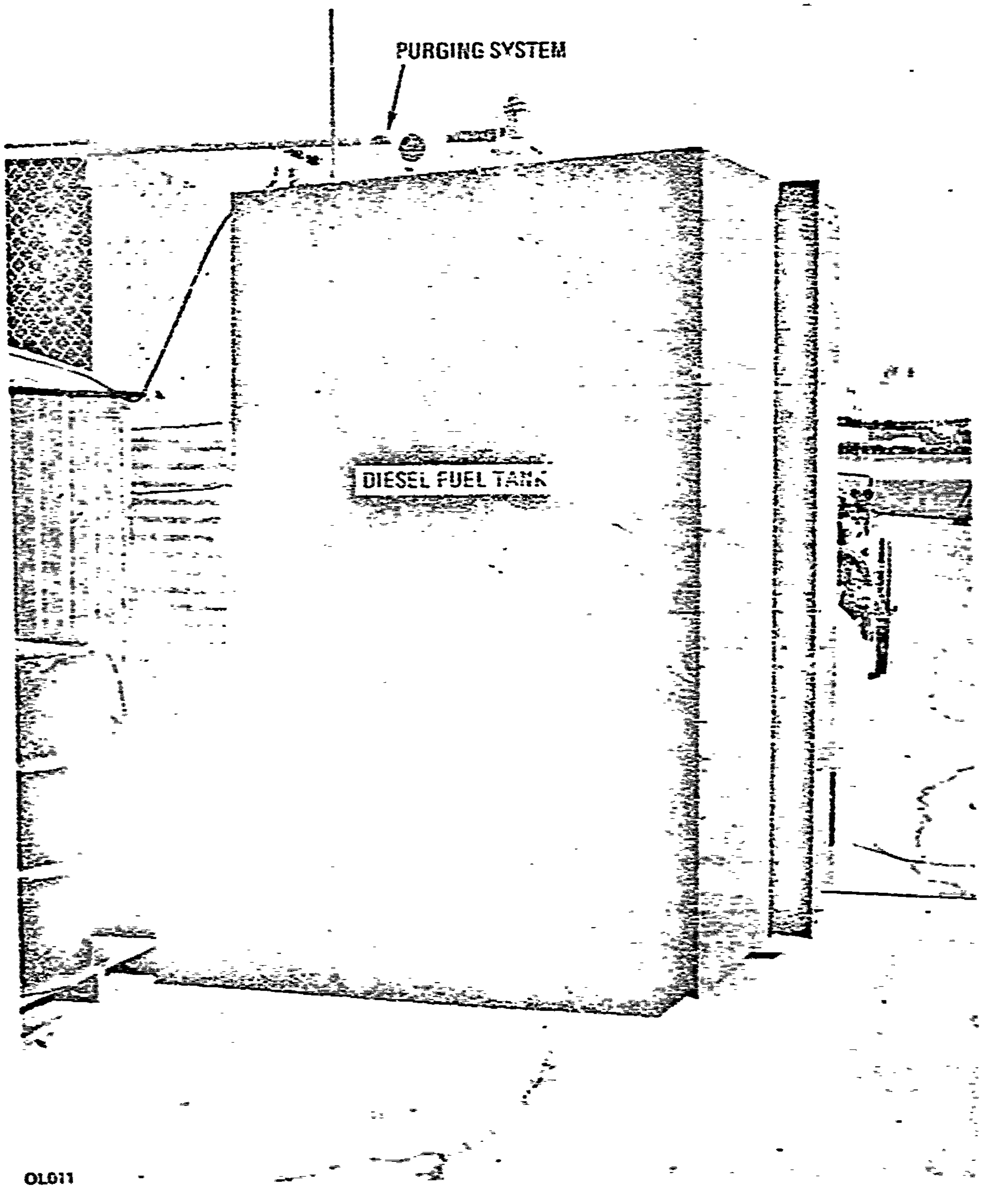

Figure 3-5. Dry Nitrogen Purging System and Fuel Tank

3.5 ELECTRICAL LOAD FOR TESTS

The electrical load in the Large Navigational Buoy (shown previously in Figure 2-5) consists of both constant current and variable current subsystems. For test purposes, the following loads were connected to the engine generators under test to first simulate and then exceed the loading they would experience in actual use aboard an LNB.

a. Engine Generator No. 1, Endurance Testing

HOURS	LOAD
0 to 13,000	Steady, 10 amperes
13,000 to 24,557	4-second cycles, 10 to 30 amperes

b. Engine Generator No. 2, Exercise Testing

HOURS	LOAD
0 to 6732	Steady, 9 amperes

Load banks for the steady load conditions consisted of multiple 250-watt heat lamps. The cold start tests on Engine Generator No. 2 also used a steady load, in this case, 9 amperes. The cycling load was accomplished by continuously operating a 10-ampere resistive heating coil, and periodically (every 4 seconds) adding 20 amperes through use of a timer. Figure 3-6 illustrates this operation.

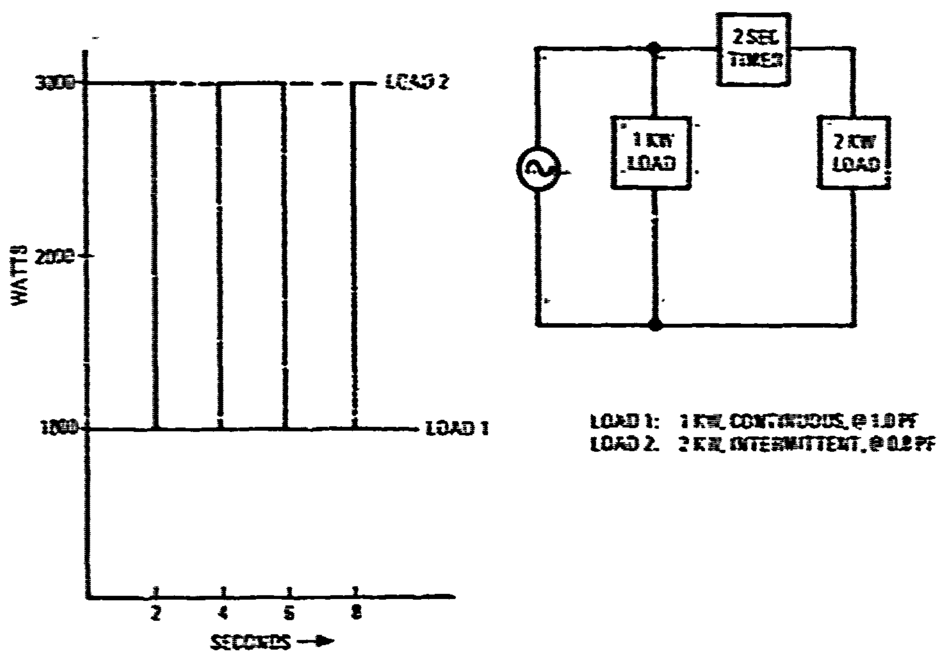

Figure 3-6. Endurance Test Electrical Load

4. DISCUSSION OF TESTS AND TEST RESULTS

4.1 ENDURANCE TEST OF ENGINE GENERATOR NO. 1

The purpose of this test was to verify the longevity and structural integrity of the engine-generator combination selected for installation in the Large Navigational Buoy. The test began in September 1969 so as to accumulate as much operating time as possible prior to the delivery of LNB No. 1 in July 1970. The testing was also intended to provide planning data for the overhaul schedule of the LNB power units. The endurance test was directed at operating the engine generator under load, continuously, until operational difficulty was encountered. Two objectives were set: the first was to achieve 6000 hours of continuous operation without failure or maintenance, and the second objective was to operate the engine for 17,000 hours without overhaul or major structural failure in the engine or generator.

- The first objective was met and exceeded when the engine operated for 9000 hours under a steady load of 1 kW before an injector malfunctioned and required replacement.
- The second objective was reached on 29 August 1971 when the engine had logged 17,000 hours. The test was then continued (under cycling load conditions) until the engine had logged 24,557 hours of operation, at which time the engine showed evidence of injector fouling. In view of the accumulated time (almost three years of continuous operation) the decision was made to terminate the test and dismantle the engine for inspection.

The cyclic loading condition was initiated after approximately 18 months of endurance testing under the steady load condition to evaluate engine performance under varying load conditions more extreme than actually experienced aboard the LNB. One load cycle is defined as the constant application of a 1000 watts (unity power-factor load); with an additional 2000 watts (0.75 leading power-factor load) alternately applied for 1.1 time constants, then removed for 1.1 time constants. A time constant is the period of time required for the generated voltage and frequency to become steady after an abrupt (step function) change in engine loading. Under these conditions, each complete load cycle required 4 seconds. The test objectives were then re-established to be either:

a. Accomplishment of 2 million load cycles, or

b. Operate until operational difficulty was encountered.

From 12 March 1971 through 13 July 1972, the engine generator successfully completed 10.1 million load cycles. During the entire cycling period, there were no engine-generator malfunctions and the unit operated with the same fuel injector. Late in the test (2 weeks before completion) a partial failure of the fuel injector was indicated (one of the three injector ports had become clogged). However, the engine continued operation at reduced load for the brief remainder of the test period.

As indicated in the summary of significant events (Table 4-1), the lube oil was replaced on 13 September 1970, and again on 6 January 1972. During this span of 10,589 hours, the unit consumed 14.4 gallons of lubricating oil. Average daily consumption is computed as 0.0323 gallon (or 0.26 pint). Total oil consumption includes that lost through leakage or seepage, as well as oil actually consumed. During the period measured, the unit was operated approximately 53% of the time under a steady 1-kW load, and 47% of the time under a variable (1 kW to 3 kW) cyclic load.

Summation — The approximate 3 years of continuous testing accomplished on the diesel engine generator demonstrated that the unit has long-term reliability with low maintenance requirements. Test objectives were met and exceeded. The basic unit successfully operated for nearly 9000 hours under a steady load without attention. An additional period of 11,556 hours was completed under cycling loads (10.1 million cycles) with no malfunction of the unit. During the nearly 3 years of test (24,557 hours), the lube oil was changed twice. The first change was at 9511 hours, and the second was at 20,100 hours. As indicated in the summary of significant events, maintenance was minimal. Following completion of the test on Engine Generator No. 1, the unit was disassembled and inspected, as reported later in this section.

Table 4-1. Summary of Significant Events, Engine Generator No. 1

DATE	ENGINE OPERATING TIME	REMARKS
9/12/69	108 hrs	Start test and log. 1.2 kW steady load.
9/26/69	443 hrs	Leaking oil seals and high engine operating temperatures. Excess oil in crankcase. Subsequent relocation of lube oil tank and increased size of drain line corrected this condition. Test was stopped and oil seals replaced at 1167 hrs (28 October 1969). Test was restarted, and ran successfully for more than 6000 hrs.
6/23/70	6,871 hrs	Replaced 12 gallons of lube oil to correct earlier fuel dilution.

Table 4-1. Summary of Significant Events, Engine Generator No. 1 (Continued)

DATE	ENGINE OPERATING TIME	REMARKS
10/8/70	9,407 hrs	Engine losing power. Re-adjusted speed control to 1800 rpm.
10/13/70	9,509 hrs	Engine losing power. Fuel injector nozzle clogged.
10/13/70	9,511 hrs	Changed injector; test resumed. Lube oil replaced, 22 gallons, 20W/40.
11/24/70	10,503 hrs	Exhaust/intake manifold retaining nuts loose. Secured nuts without stopping test. Instituted assembly check to prevent recurrence.
1/22/71	11,905 hrs	Engine speed control locknut loosened. Re-tightened.
3/8/71	13,001 hrs	Engine shutdown for generator modification to external voltage control unit.* Fuel and lube oil filters replaced. Oil bath air cleaner cleaned and replaced. Fuel injector replaced. Engine inspected for leaks and tightness. Test electrical load modified for cyclical load (10 to 30 amps) at 4 sec intervals (1 kW - 3 kW). * An improvement to the LNB generator control configuration.
3/17/71	13,034 hrs	Test resumed after 33 hrs of checkout.
8/29/71	17,000 hrs	Two years operating time.
1/6/72	20,100 hrs	Changed lube oil, 22 gallons, 20W/40.
3/6/72	21,500 hrs	2-1/2 years operating time.
6/29/72	24,269 hrs	Partial injector failure, engine continued operation under reduced load.
7/13/72	24,557 hrs	Test completed after nearly 3 years of operation. Engine removed for disassembly and inspection.

4.2 COLD START AND EXERCISE TESTS OF ENGINE GENERATOR NO. 2

The test configuration of Engine Generator No. 2 was the same as that for Engine Generator No. 1. Two series of tests were planned for this unit, including six cold starts, and an indefinite number of exercise cycles. The series of tests were commenced in April 1970, and was concluded on 6 January 1972. The tests were conducted in the same facility used for Engine Generator No. 1, and the two test units shared fuel tank and starting batteries.

The purpose of periodic exercising (on-off sequencing) and cold start testing was to verify the starting ability of the standby LNB engine-generator unit when subjected to low ambient temperatures and long periods of idleness. Testing of Engine Generator No. 2 was done in parallel with the engine endurance testing performed on unit No. 1. The following paragraphs summarize the tests performed on this unit.

4.2.1 COLD START TESTS

The purpose of these tests was to establish the starting characteristics of the units when subjected to low ambient temperatures, and confirm the capability of the standby buoy engine to start in cold weather. These tests were performed with the engine generator mounted in the van shown in Figure 3-4.

Three starts were made at approximately 30°F and three starts at approximately 40°F. One start was made per week with the engine operating for 1 hr under a 1-kW load after each start. The outdoor relative humidity was in excess of 50% during each start. After 6 weeks of testing, an additional series of starts was made at 9°F to further evaluate the unit. Number 2 diesel fuel was used in all testing.

Cold start tests were accomplished in April, May, and June of 1970. Prior to commencement of each test, the engine generator, lube oil tank, and the fuel supply were cold soaked and stabilized at each desired temperature. Temperature probes recorded temperatures at the cylinder head, in the lube oil reservoir, in the crankcase, and in the ambient air (inside cold box). Data were measured and recorded for each start and included:

a. Time required for ignition

b. Maximum starter current

c. Crankcase oil temperatures

d. Lube oil reservoir temperature

e. Cylinder head temperatures

f. Outdoor humidity (U.S. Weather Bureau)

Tabular results of the cold start tests are presented in Table 4-2.

Table 4-2. Cold Start Tests

TEST NO.	TEMP. °F	VOLTS MIN.	STARTER AMPS (MAX)	STARTER AMPS (AVG)	TIME TO IGNITION (SEC)	TIME TO GENERATOR FULL OUTPUT (SEC)	CRANKING RPM
1A	70	13	375	125	1-1/4	-	420
1B	25	12	380	100	3-3/4	-	420
1	32	12.5	390	100	4-1/4	-	420
2	30	12.5	370	120	5	17.5	420
3	26	12.5	330	110	4	16	420
4	37	12.5	340	100	2	14	420
5	39	12.5	-	-	2.5	30	420
6	37	12.5	300	-	4	20	380
7	9	12.5	-	-	28	42	280-400

4.2.2 EXERCISE TESTS

Exercise testing of Engine Generator No. 2 was commenced after completion of the cold start testing on 5 June 1970. All tests were with a 1 kW load. The following schedule of testing was accomplished.

		BEGIN	END
a.	Two months running	6/5/70	8/10
b.	Two weeks standby (stopped)	8/10	8/24
c.	Two months running	8/24	10/23
d.	Two weeks standby	10/23	11/6
e.	Two months running	11/6/70	1/7/71
f.	Two weeks standby	1/7/71	1/21
g.	Six weeks running	1/21	3/8/71

On 8 March 1971 this series of tests was terminated and the generator modified to external voltage regulation. Minor servicing and maintenance was performed on the engine, and the fuel injector was replaced with a new unit.

A revised schedule of exercise testing was commenced on 16 March 1971. This accelerated the number of exercise cycles to a nominal three per working day. The engine was shut down at night. To perform an exercise sequence the engine was started, run to stabilized temperature, stopped, and allowed to cool until the cylinder head temperature was within 5°F of the ambient air temperature. The engine was considered stabilized when the voltage and frequency were within the specified limits or when cylinder heat temperature transients were no longer apparent, whichever was later. As of 6 January 1972, 1079 cycles had been completed.

On 21 September 1971, the unit was equipped with an automatic starting and timing device to permit around the clock test operations. The number of starts was thereby increased from a nominal three per working day to eight starts every day. On 17 October 1971, the unit was stopped to clean up oil spillage. The lube oil filler cap had been improperly secured, had subsequently loosened, and allowed oil mist to escape from the oil filler opening on top of the cylinder head cover. The test was resumed on the following day. There were no other failures or malfunctions during the remainder of the test. This unit operated for 6732 hours during the total start and exercise test sequence.

During periods of operation, the engine temperature and the generator output amperage, voltage, and frequency were measured and recorded three times per day. The time between the first and last measurement each day was no less than 8 hours.

A spectrochemical test and a physical test were performed on the lube oil immediately prior to the end of each period of engine operation in the exercise tests. The findings of the spectrochemical and physical tests indicated that no significant deterioration of the oil had been experienced.

Summation — The cold start tests showed that the engine generator unit in the standby mode is capable of starting at the ambient temperatures expected during Large Navigational Buoy operations (30°F in the engine compartments). No engine modification or special equipment was required to accomplish the cold starts.

The exercise tests performed revealed no adverse affects on engine generator performance due to intermittent operation. Carbon fouling of the injector was less than expected for this loading (1 kW) and did not appear to be an important factor for future operation of these units in this mode.

The results of the final disassembly inspection are given in paragraph 4.3.2.3 of this report, together with photographs of the injector removed after 1318 hours of intermittent operation. The engine unit had operated for a total of 6732 hours at the completion of testing, as indicated in the summary of significant events for Engine Generator No. 2 presented in Table 4-3.

Table 4-3. Summary of Significant Events, Engine Generator No. 2

DATE	ENGINE OPERATING TIME	REMARKS
4/30/70	0	Commenced cold start tests.
6/5/70	6.9	Commenced exercise testing.
6/29/70	576	Injector failure. Injector replaced with new unit.
3/8/71	5514	Completion of first exercise test phase. Fuel injector routinely replaced.
3/16/71	5514	Started accelerated second exercise testing phase (nominal three starts/day).
10/17/71	6198	Shut down to clean up oil leak. Oil filler cap vibrated off cylinder head cover.
10/21/71	6244	Engine on automatic cycling timer (nominal eight starts/day). 508 starts to date.
1/6/72	6732	Completed test. Engine disassembled and inspected for wear. 1079 starts completed.

4.3 TEST DATA

Log sheets from the series of tests performed on Engine Generator No. 1 and Engine Generator No. 2 are bound in Part 2 of this report. The following paragraphs give the results of various inspections and trouble investigations during the course of the tests.

4.3.1 ENGINE GENERATOR NO. 1

4.3.1.1 REPORT NO. 1

Date:	26 September 1969
Engine Generator Unit	No. 1
Hour Meter Reading:	443 hours

Observations — Engine temperatures (oil and cylinder head) showed an abrupt increase on 26 September 1969. At the same time, an oil seepage developed at the camshaft extension seal at the front of the engine. The oil seal housing was also found to be rotating with the camshaft.

Cause — Investigation subsequent to the failure showed an abnormal amount of lubricating oil present in the engine crankcase. During operation, the crankcase was found to contain 5 quarts of lubricating oil, whereas the normal sump crankcase capacity is only 5 pints. The oversupply of oil had caused excessive loading and overheating of the engine. The overheating had, in turn, caused failure of the camshaft oil seals.

Corrective Action — The symptoms of the failure were as noted. The cause of the failure was traced to insufficient drainage capability from the crankcase to the externally mounted lube oil reservoir. Corrective action was taken to:

a. Lower the lube oil reservoir with respect to the engine generator assembly

b. Increase the size of the lube oil drain hose from 5/8-inch I.D. to 3/4-inch I.D.

No further problems were encountered with the lubrication system during the test. The final lube oil line arrangement is shown in Figure 4-1.

4.3.1.2 REPORT NO. 2

Date:	12 September 1970
Engine Generator Unit:	No. 1
Hour Meter Reading:	9486

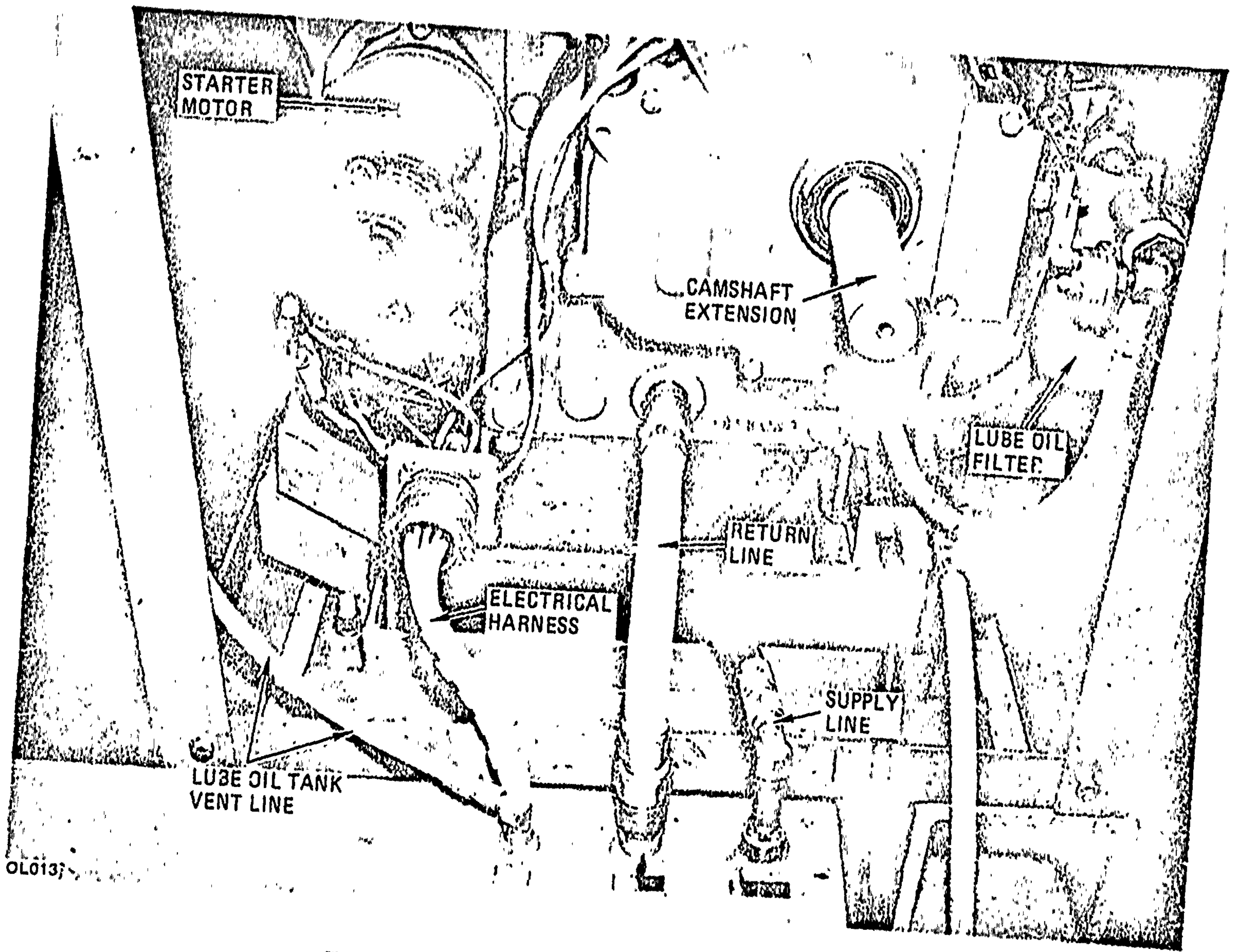

Figure 4-1. Final Lube Oil Line Arrangement

Observations — Engine lost power, which was reflected in reduced rpm under load. Voltage and frequency were out of limits (108V and 58 Hz) and could not be brought back by the engine speed adjusting screw.

Cause — Injector nozzle was removed and injector holes were found to be partially blocked by carbon deposits.

Corrective Action — Replaced injector at 9511 hours.

4.3.1.3 REPORT NO. 3

Date:	24 November 1970
Engine Generator Unit:	No. 1
Hour Meter Reading:	10,503 hours

Observations — Routine inspection revealed loose retaining nuts on exhaust/intake manifolds.

Cause — Unknown

Corrective Action — Re-torqued three nuts

4.3.1.4 REPORT NO. 4, INSPECTION

Date:	9 March 1971
Engine Generator Unit:	No. 1
Engine Hours:	13,001 (hours on injector, 3490)

Note

This unit was stopped and inspected during the generator external voltage control modification.

Inspection Item Accomplished:

a. Changed fuel filter element.

b. Changed lube oil filter element.

c. Washed air cleaner screen.

d. Replaced fuel injector with new unit.

e. Cleaned carbon deposits from exhaust plenum and combustion exhaust pipe.

f. Tool oil sample.

g. Installed gasket on valve cover (none previously).

h. General inspection of engine exterior for leaks and loose connections. Tightened nuts and bolts.

Comments on Items:

a. Fuel filter was inspected; no visible contamination. Element was replaced.

b. Lube oil filter element was removed and replaced. No visible contamination.

c. Air cleaner unit was inspected and found to have minor amounts of sediment in the bottom of oil reservoir. Screen appeared to be clean. Washed screen and replaced.

d. Fuel injector was removed and photographed (see Figure 4-2). Carbon buildup on nozzle was blocking fuel inlet ports (Figure 4-3). Replaced with new, factory tested injector assembly. Figure 4-4 illustrates a new injector nozzle for comparison with Figure 4-3.

e. The engine exhaust plenum (at junction of flexible exhaust hose) had accumulated granular carbon particles. The combustion exhaust pipe was partially blocked by sooty deposits, especially around the temperature probe. Photographs were taken of these deposits, and are included with this report as Figures 4-5 and 4-6. The plenum and exhaust pipe were cleaned and reassembled. The accumulations shown in Figures 4-5 and 4-6 had no discernible effect on engine operation.

f. A lubrication oil sample was taken for analysis. The lube oil reservoir level was measured and found to be unchanged from that measured on 9 October 1970.

g. Several miscellaneous bolts were found to be loose and were tightened. The "banjo" fitting at the fuel pump had been seeping fuel for several weeks, so was disassembled, inspected, and re-assembled. The copper gaskets in this unit were annealed and polished prior to re-assembly. Work on the generator was limited to the actual modification required to convert the voltage regulation to external control. No generator malfunctions or anomalies were noted during this inspection.

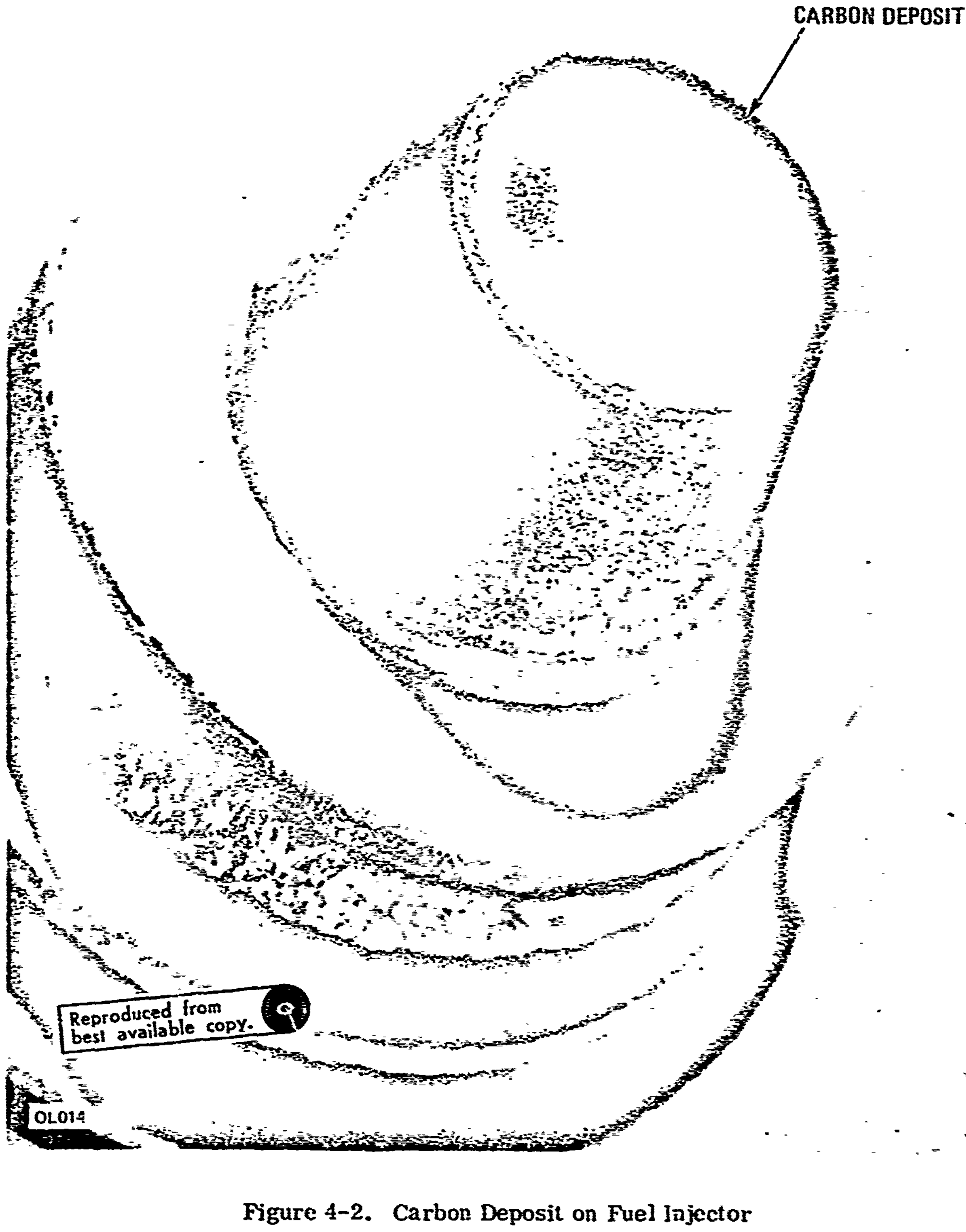

Figure 4-2. Carbon Deposit on Fuel Injector

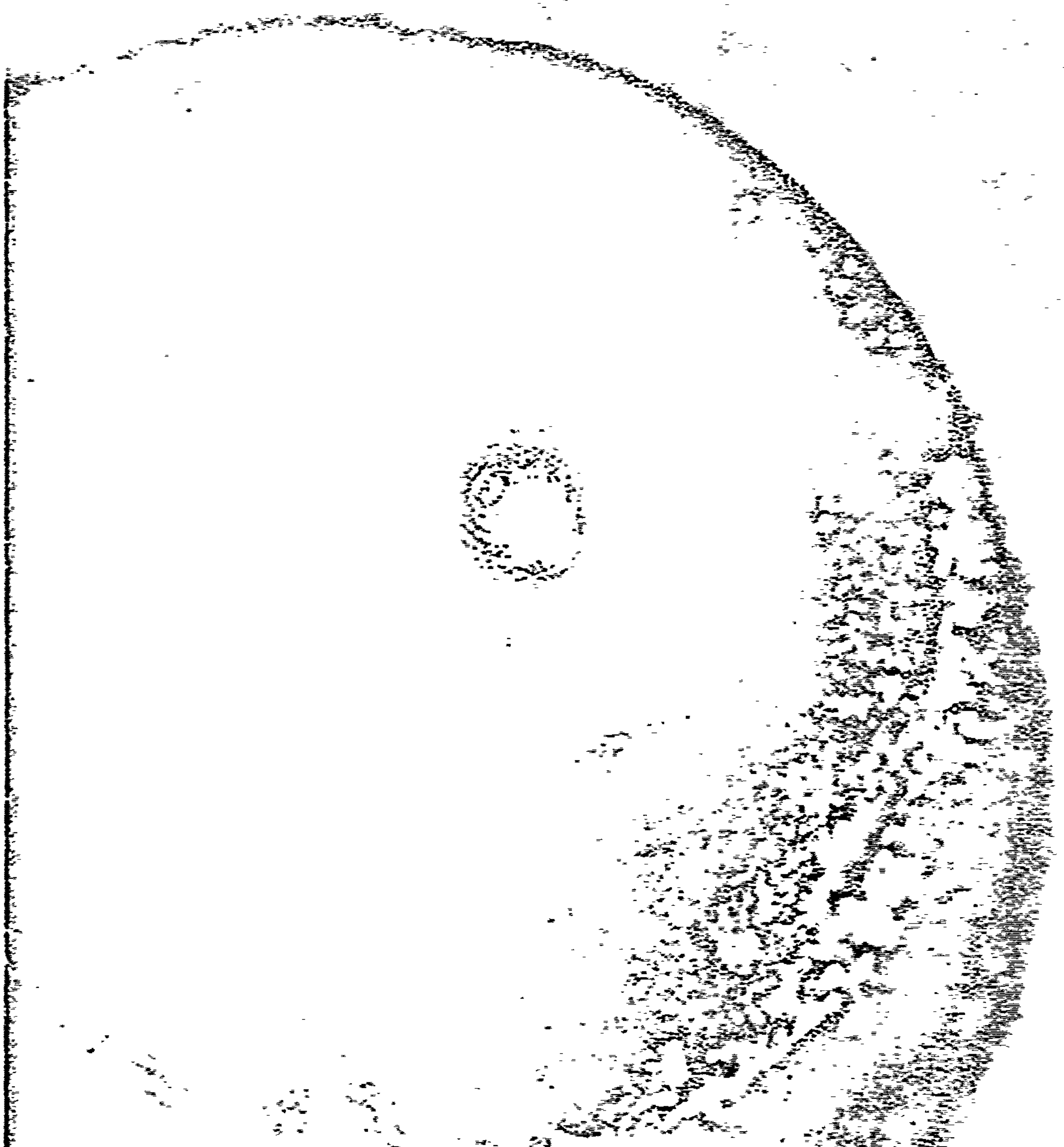

Figure 4-3. Carbon Deposit on Nozzle

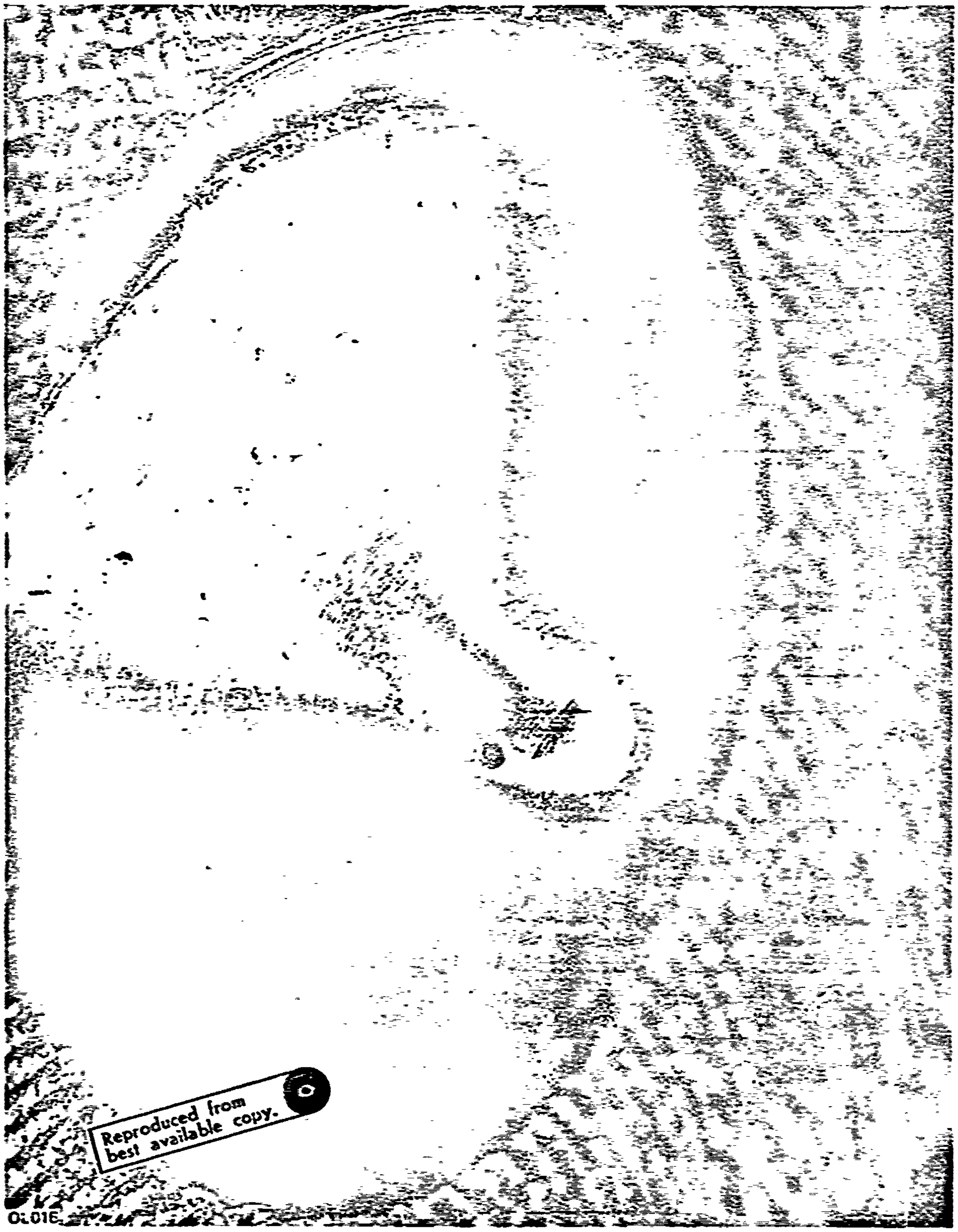

Figure 4-4. New Nozzle

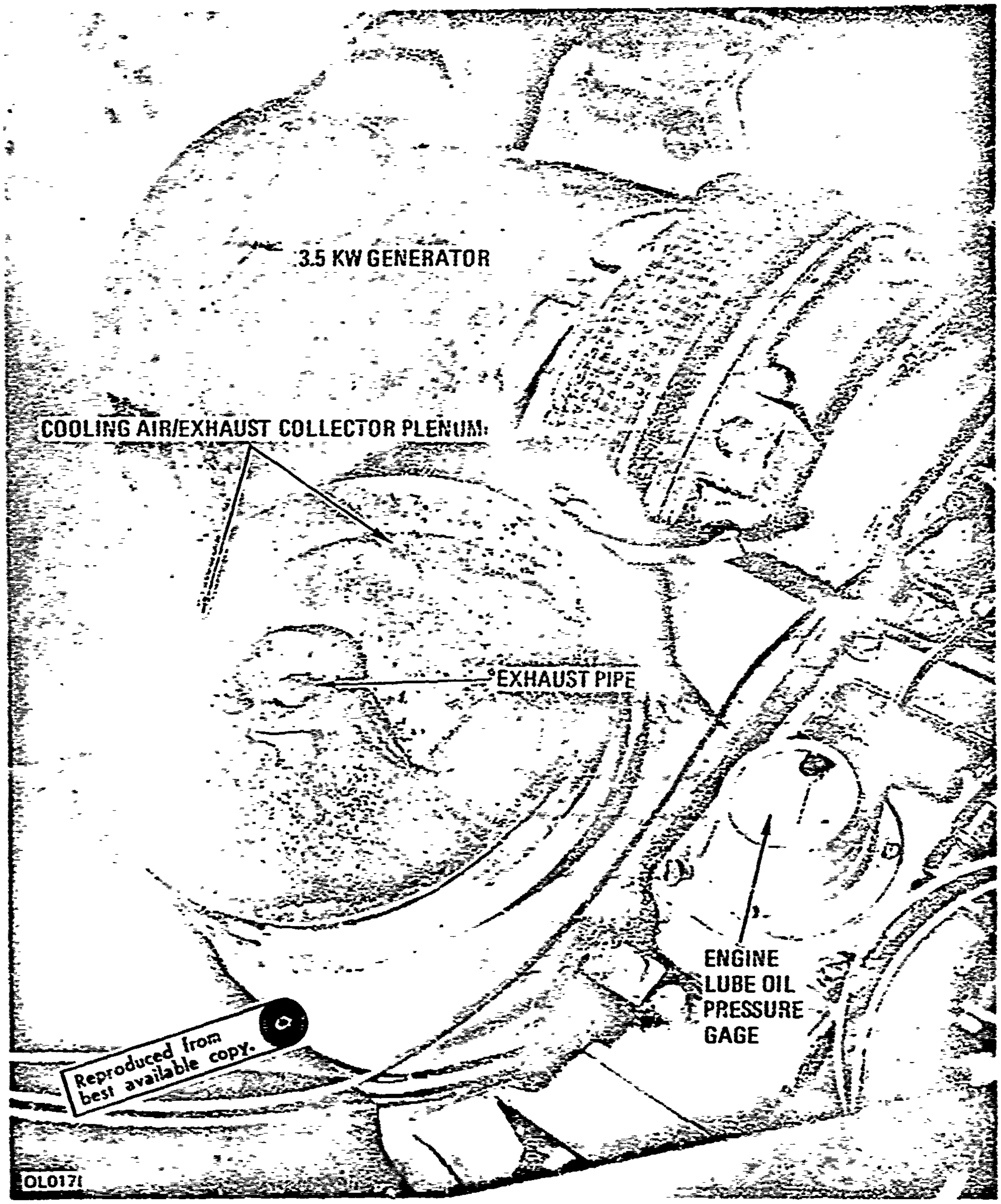

Figure 4-5. Carbon Buildup in Plenum

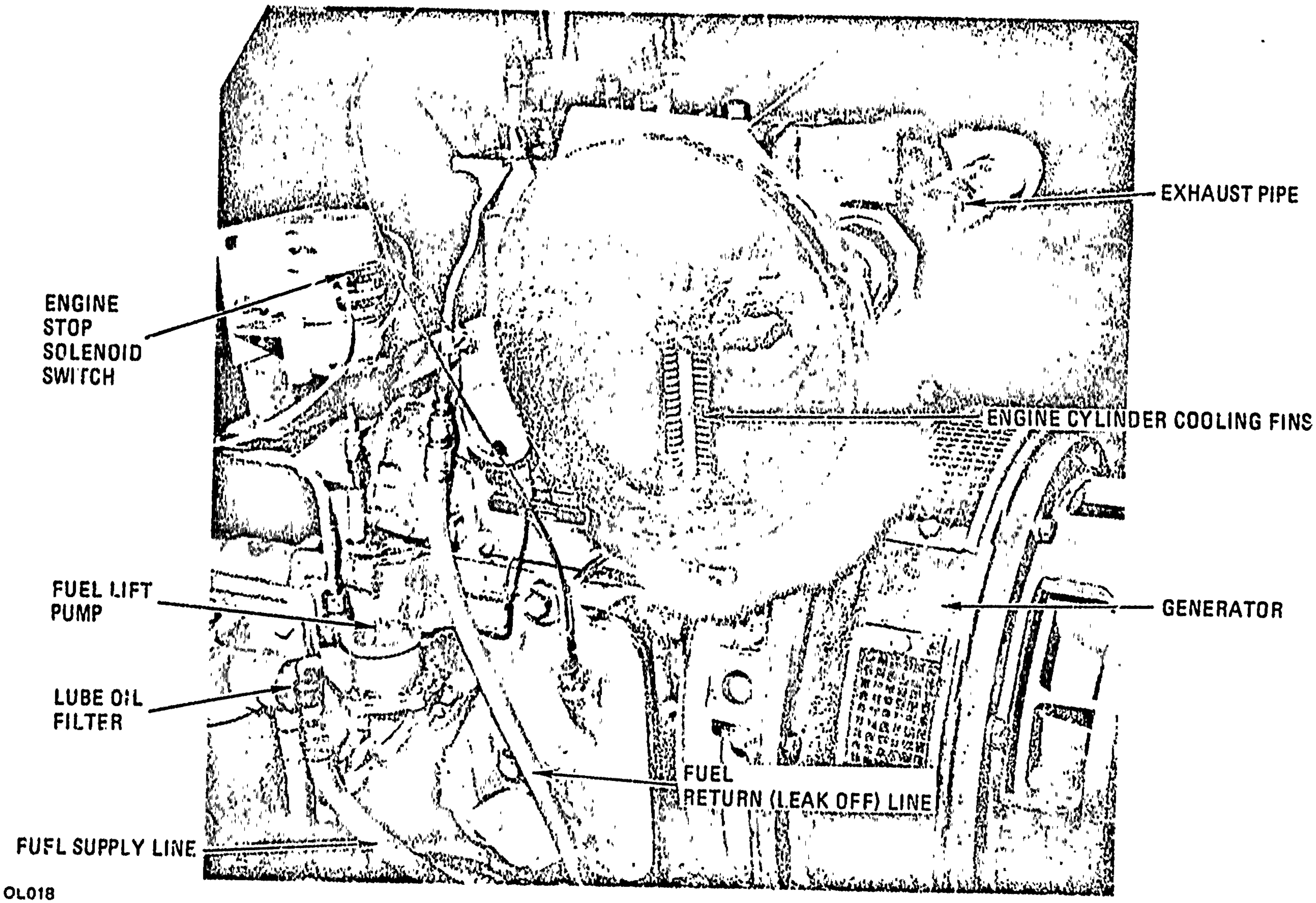

Figure 4-6. Carbon Accumulation in Plenum

4.3.1.5 REPORT NO. 5, FINAL DISASSEMBLY AND INSPECTION

Date:	13 July 1972
Engine Generator Unit:	No. 1
Engine Hours:	24,557 (hours on injector, 11,556)

General — The engine generator was secured on 12 July 1972 after accumulating a total running time equivalent to 2.8 years at conditions more severe than normal LNB service. Shortly previous to the conclusion of the test (at 24,269 hrs) the engine showed an inability to maintain 1800 rpm at a peak electrical load of 29 amperes. For this reason (except for a brief unloaded period) the unit was operated at a constant load of 10 amperes for the remainder of the test.

On 13 July 1972, the unit was disassembled for final inspection and restoration to "as new" condition. The tear down and inspection were witnessed by U.S. Coast Guard and General Dynamics engineering representatives, and the results of the inspection are reported in following paragraphs.

Overall Condition, Exterior — The engine showed external evidence of oil seepage attributable to a combination of a minor leak at a fuel filter fitting, and a gradual deterioration of the flywheel end crankshaft journal seal. Figures 4-7 through 4-9 illustrate the condition of the exterior.

The squirrel cage blower (part of the flywheel assembly) and the cooling shrouds (except for the discharge and engine exhaust plenum area as illustrated in Figure 4-10) were found relatively free of dirt and deposits, even though the test environment was more conducive to such accumulations than the normal service conditions aboard a buoy.

During examination of the cooling system, a small section of the cooling air exhaust plenum was found cracked and separated from the main body (see Figure 4-11). Accumulation on the cooling fins was negligible, as shown in Figure 4-12 and 4-13. Maximum accumulation was observed to have occurred at the base of the cylinder, as shown on the right-hand side of Figure 4-13. (Note that apparent accumulations as shown in Figures 4-12 and 4-13 are caused by camera parallax.) The typical condition is that shown in the central area of Figure 4-12.

Overall Condition, Interior — The interior of the engine (Figure 4-14) was found to be remarkably clean. Except for the area within the rocker cover (shown in Figure 4-15), sludge deposits were virtually non-existent. Figure 4-16 shows the condition observed within the gear case. The bright metallic interior surface of the aluminum gear case cover was plainly visible through the residual oil film, as shown in Figure 4-17.

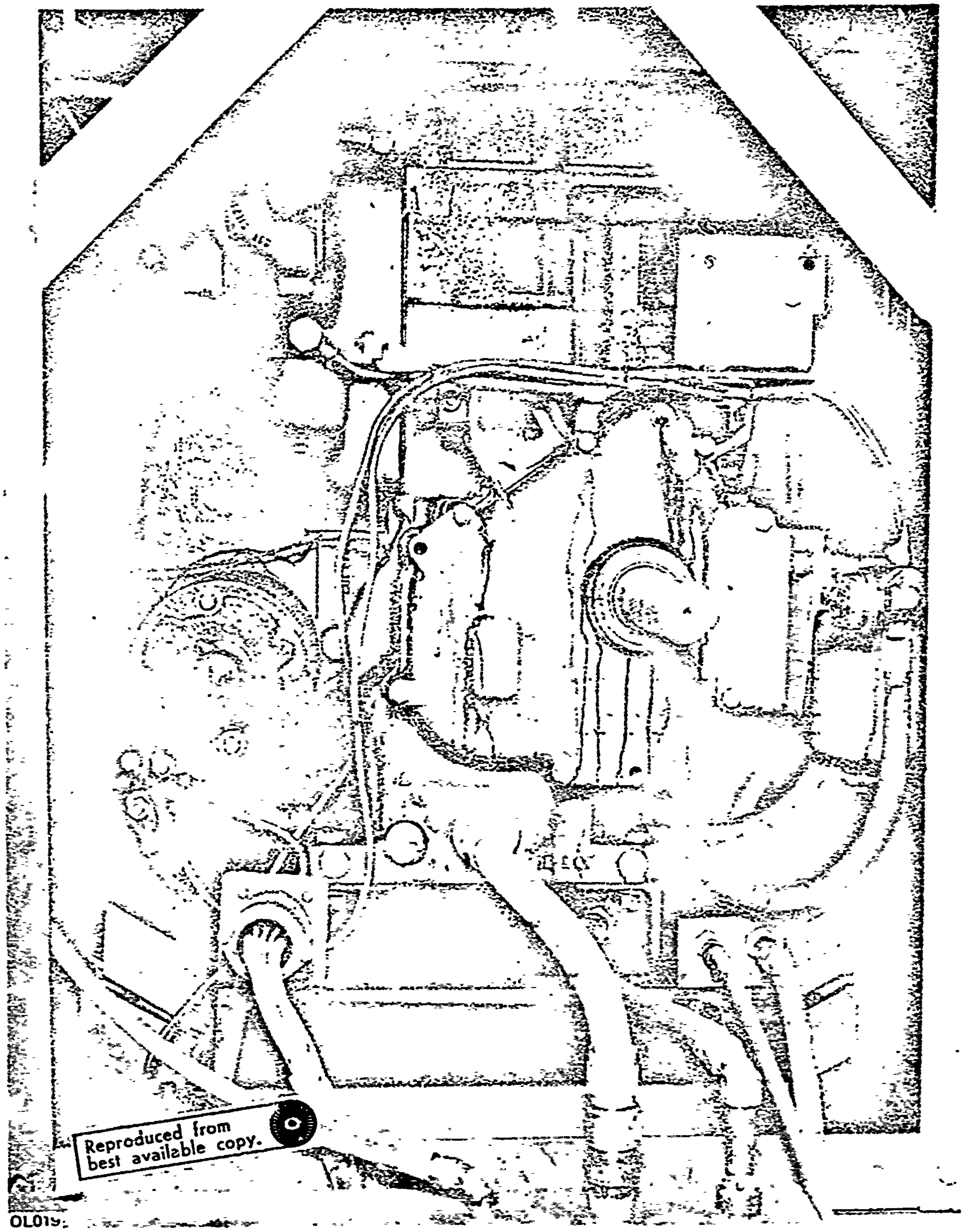

Figure 4-7. End View of Unit

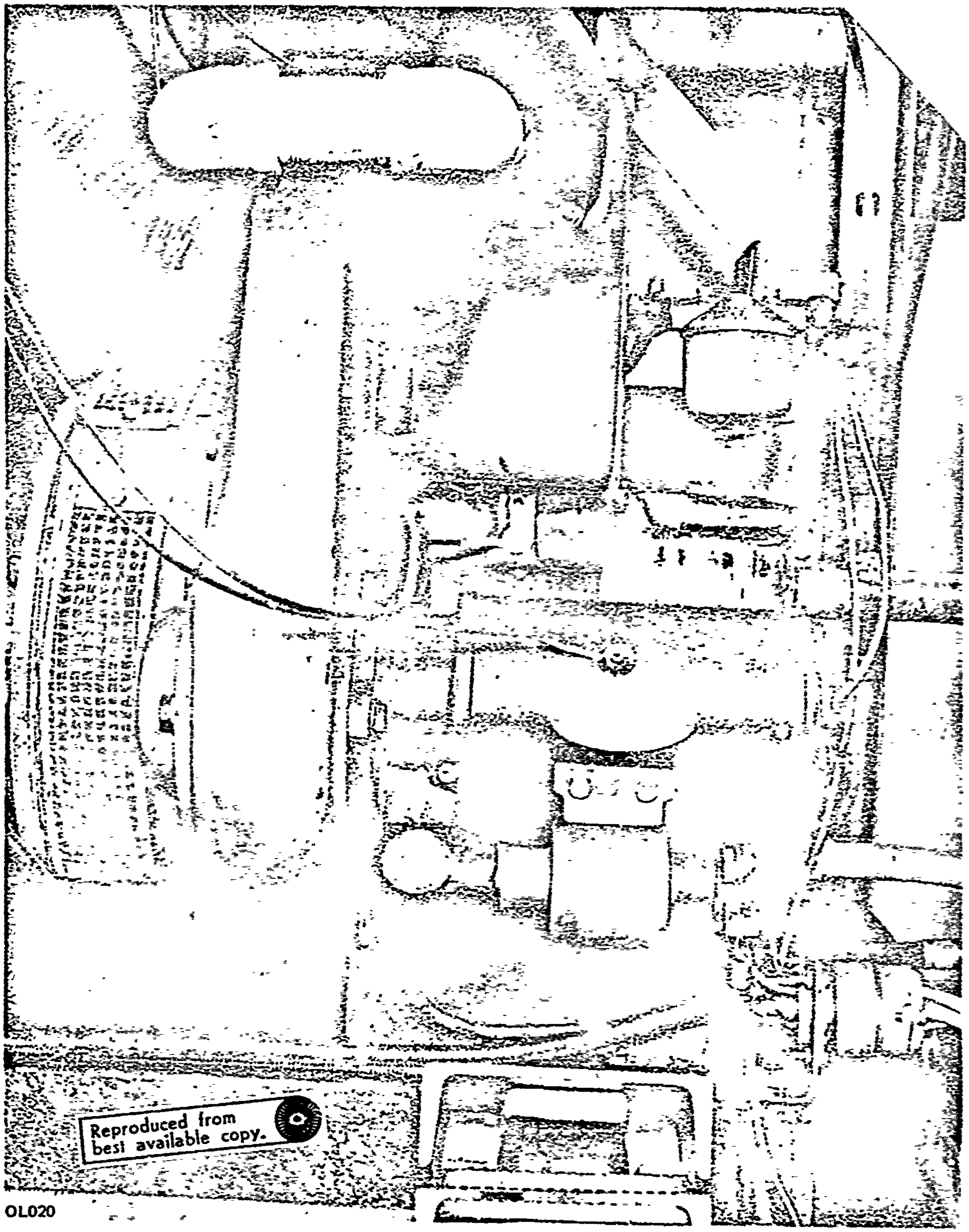

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Figure 4-8. Side View of Unit

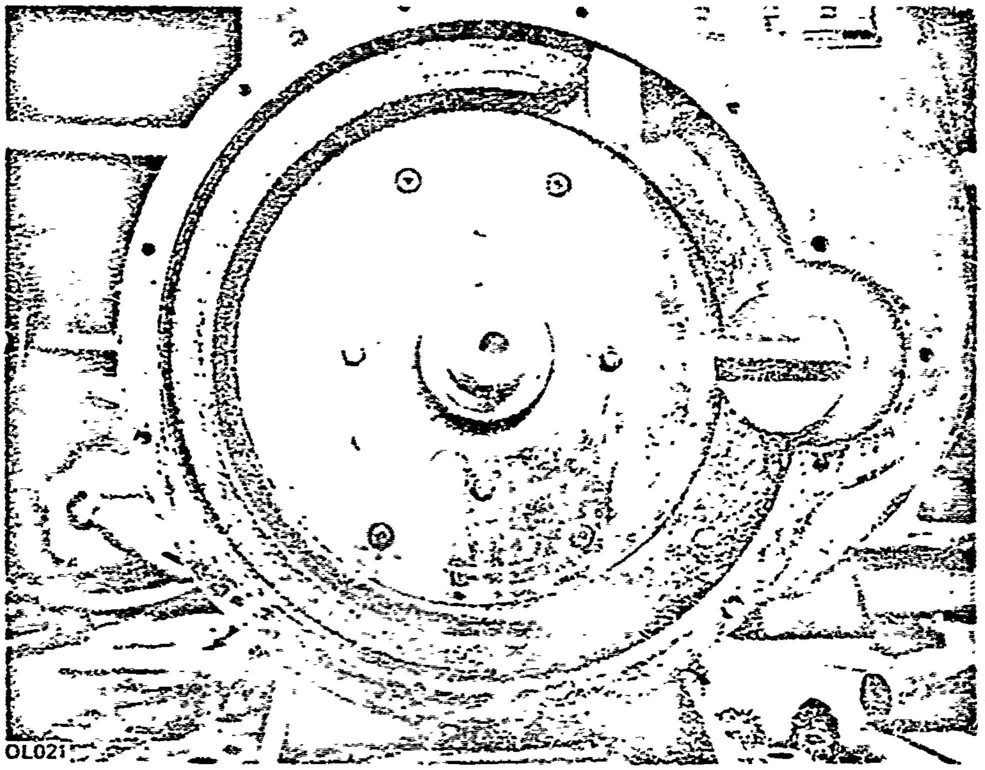

Figure 4-9. Deterioration of Seal

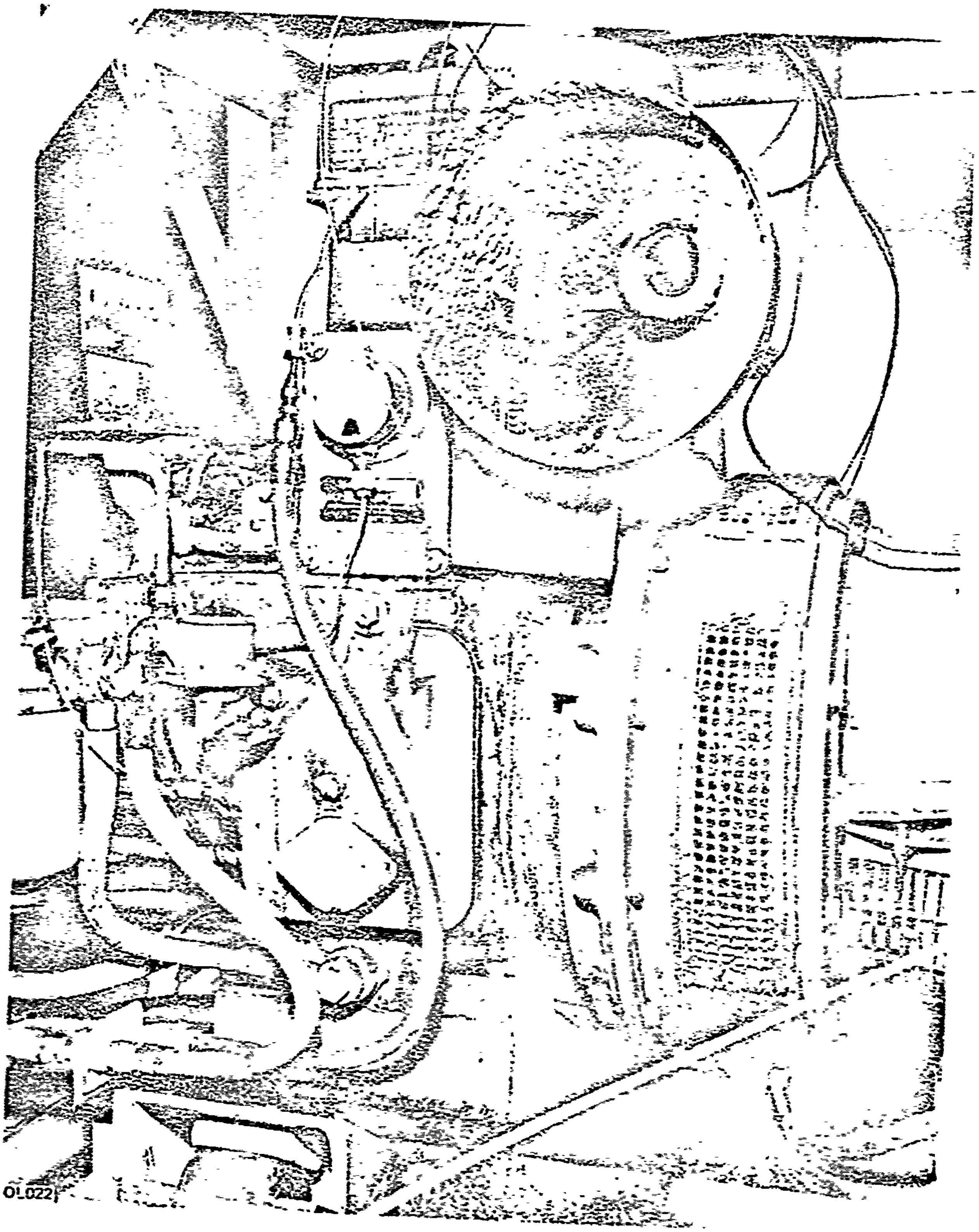

Figure 4-10. Discharge and Exhaust Plenum Area

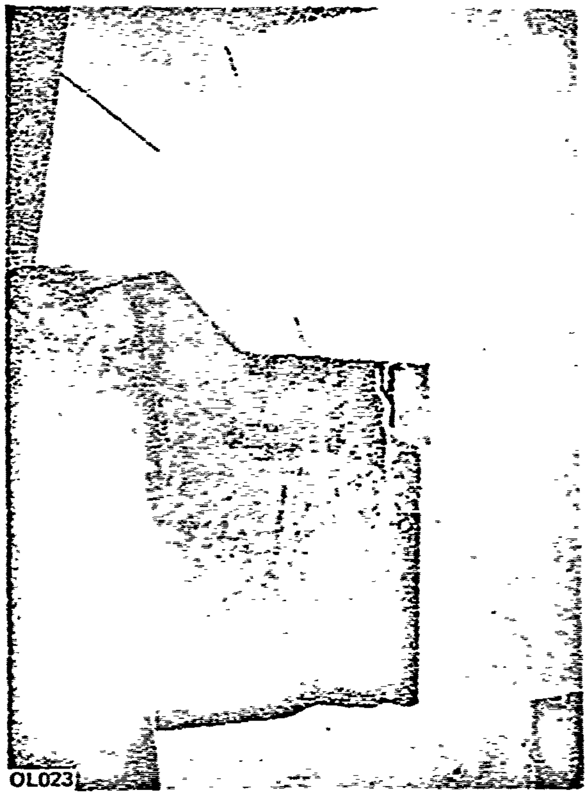

Figure 4-11. Crack in Cooling Air Exhaust Plenum

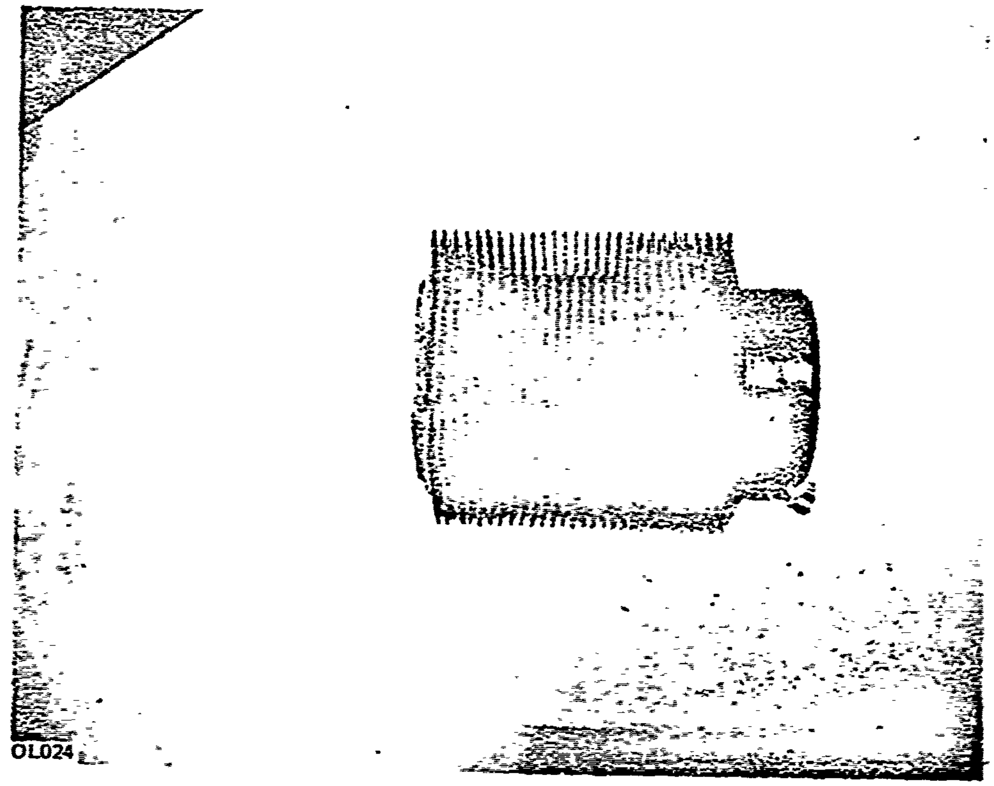

Figure 4-12. Cooling Fins, View 1

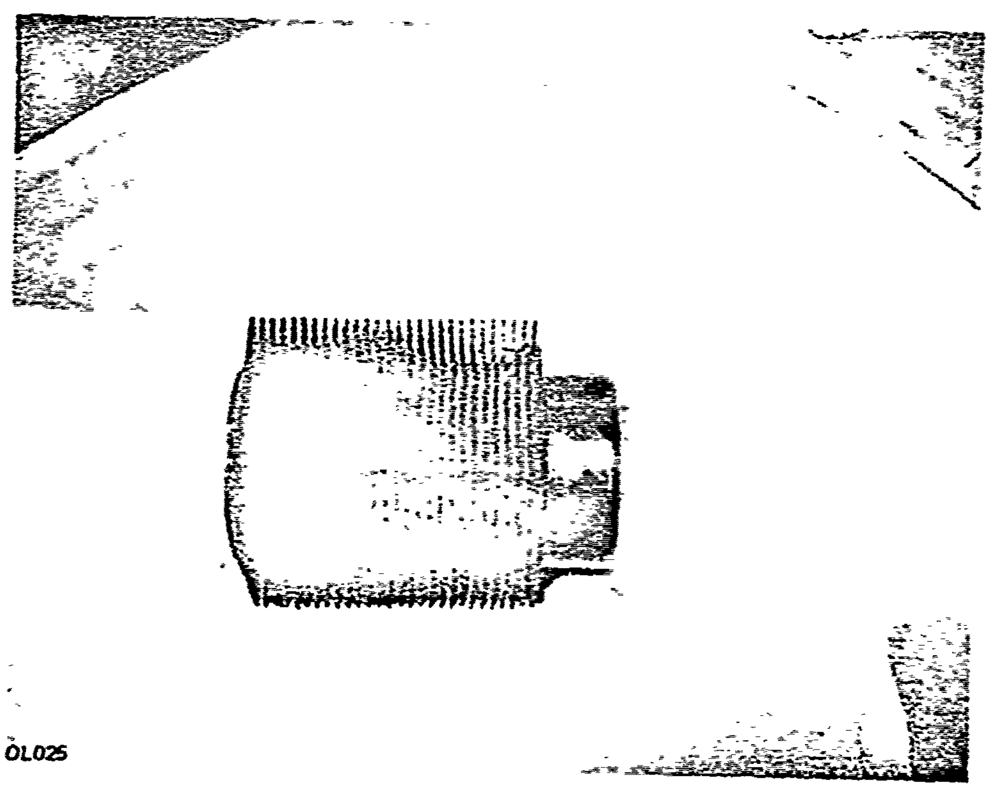

Figure 4-13. Cooling Fins, View 2

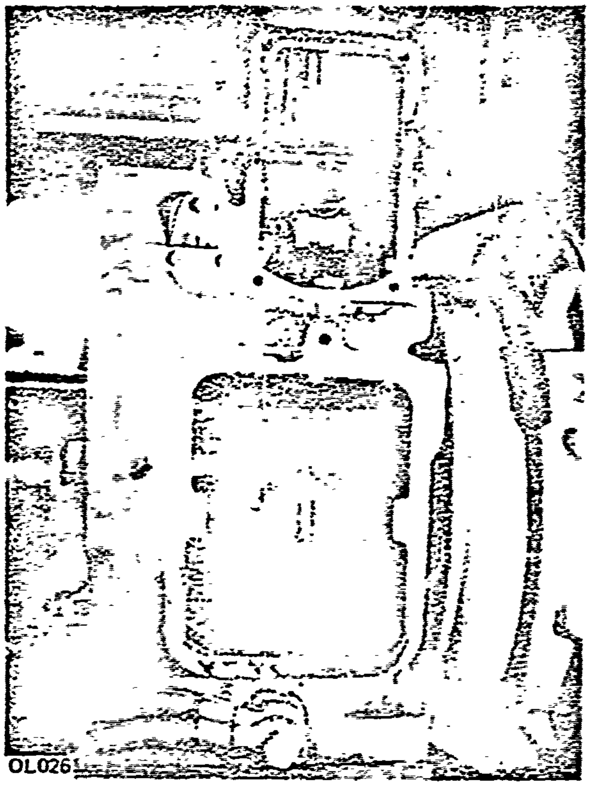

Figure 4-14. Engine Interior

Figure 4-15. Area Within Rocker Cover

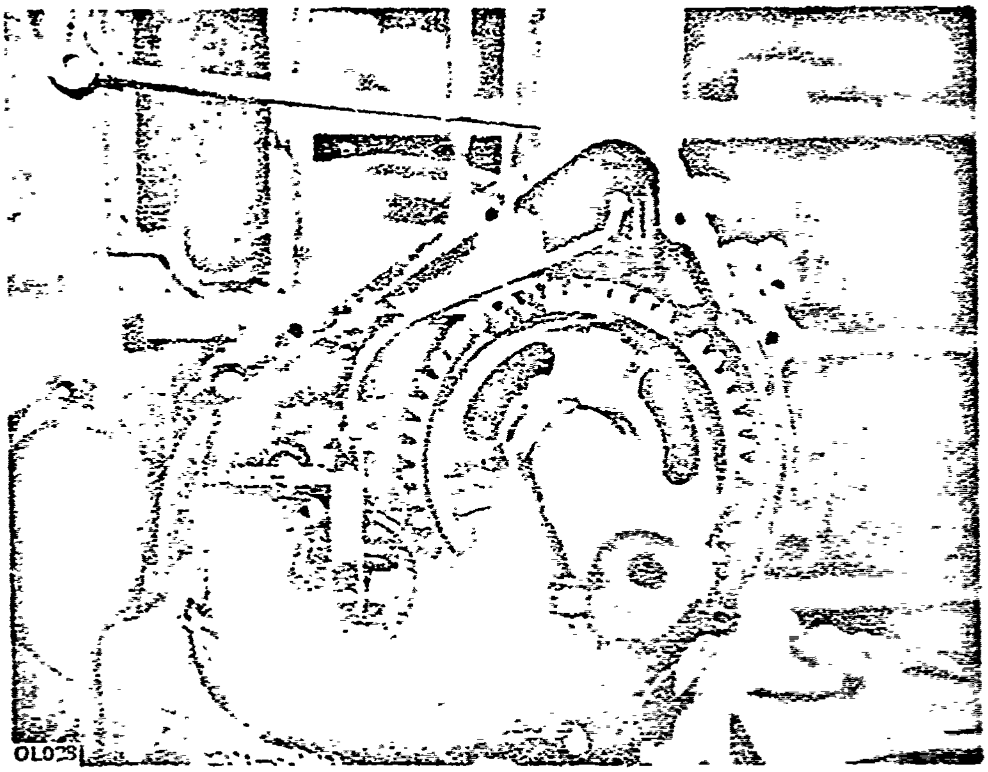

Figure 4-16. View Inside Gear Case

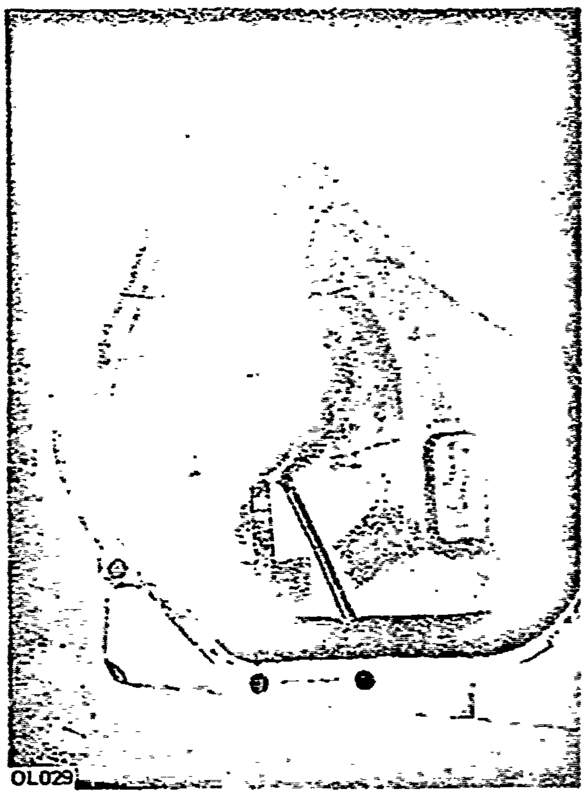

Figure 4-17. Interior Surface of Aluminum Gear Case Cover

An examination of the interior of the alternator disclosed that the only significant accumulation of foreign material (dust) was confined to the exciter end of the rotor assembly. This is shown at the right-hand side of Figure 4-18. There was no evidence of bearing seal deterioration or loss of bearing lubricant.

Cylinder Head Assembly — Carbon accumulation in the cylinder head combustion chamber was generally light. A crescent shaped area involving erosion of the head material (see Figure 4-19) was observed. Examination of the top surface of the piston disclosed a corresponding area of erosion (Figure 4-20). The cause of these conditions was attributed to an abnormality in injector spray pattern as illustrated by Figure 4-26 discussed later in the text.

Initial examination of the visible surface of the valves disclosed no evidence of burning. Upon valve removal, considerable erosion of valve faces and seats was noted (see Figures 4-21, 4-22, and 4-23). Valve clearances were not examined during disassembly. However, the absence of burning and the fact that although eroded the valve and respective seat surfaces interfaced well, suggested that pounding as opposed to insufficient clearance was the likely cause. Valve stem, guide, and port deposits of carbon were light. Considering the period of operation, stem and guide wear were minimal, resulting in clearances not exceeding 0.006 inch.

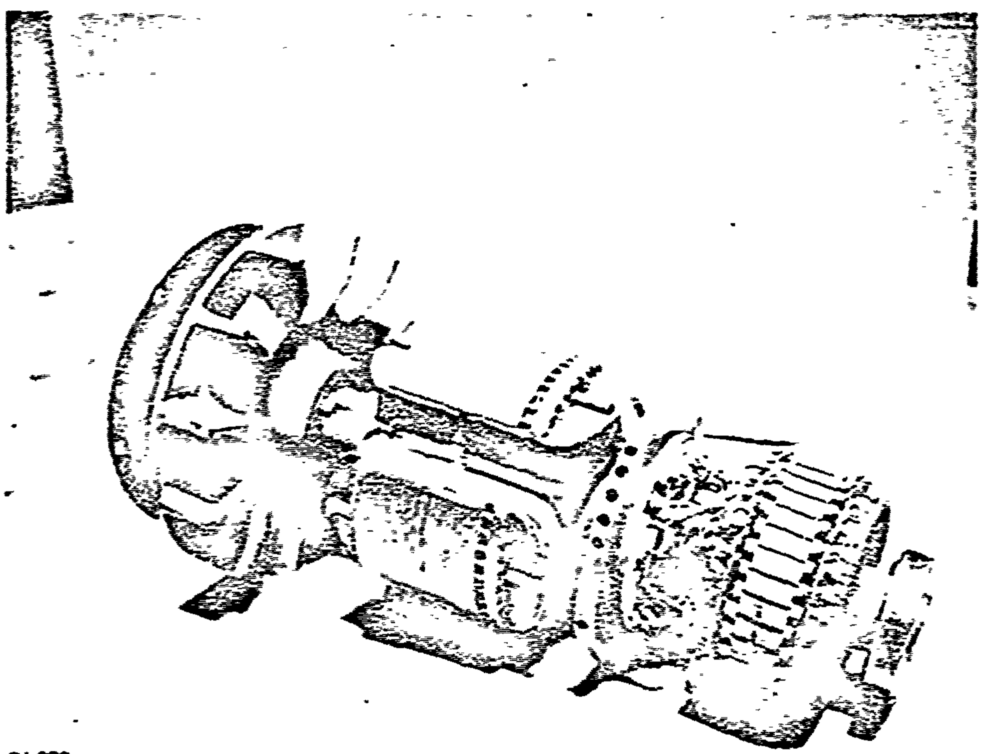

Figure 4-18. Alternator

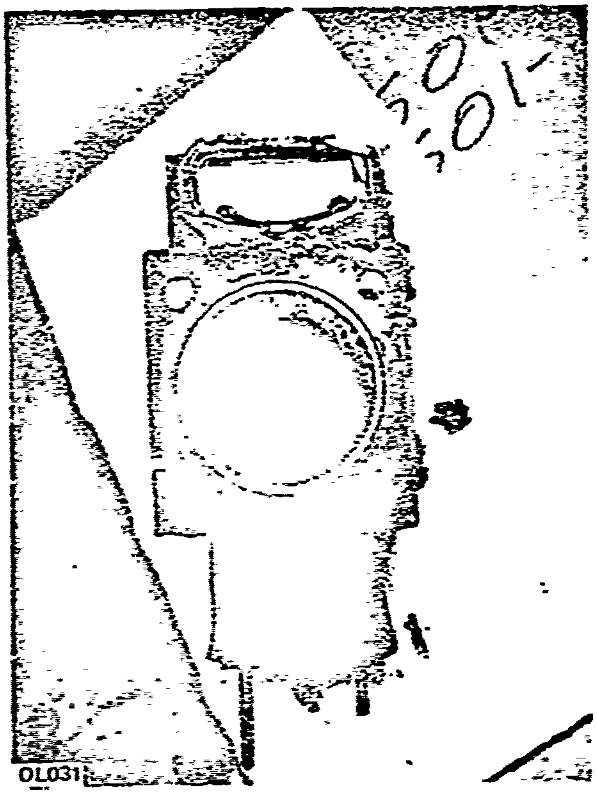

Figure 4-19. Cylinder Head

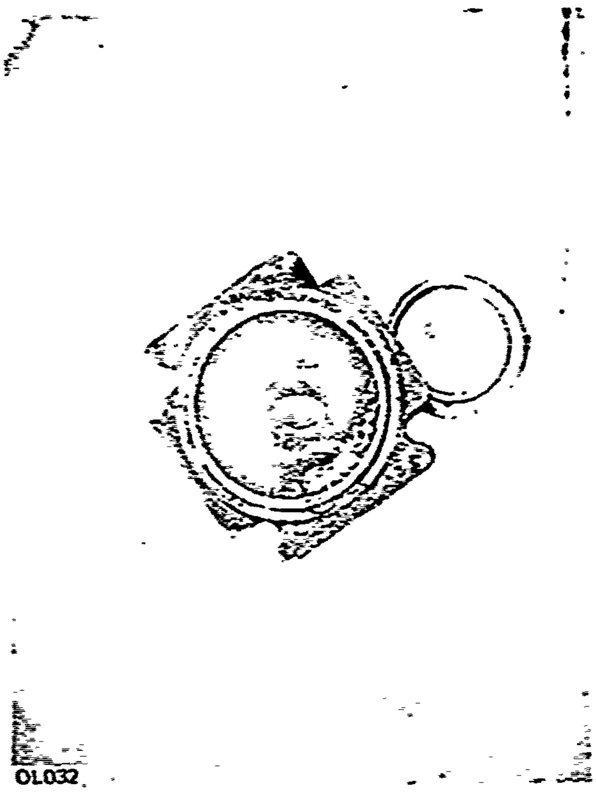

Figure 4-20. Top Surface of Piston

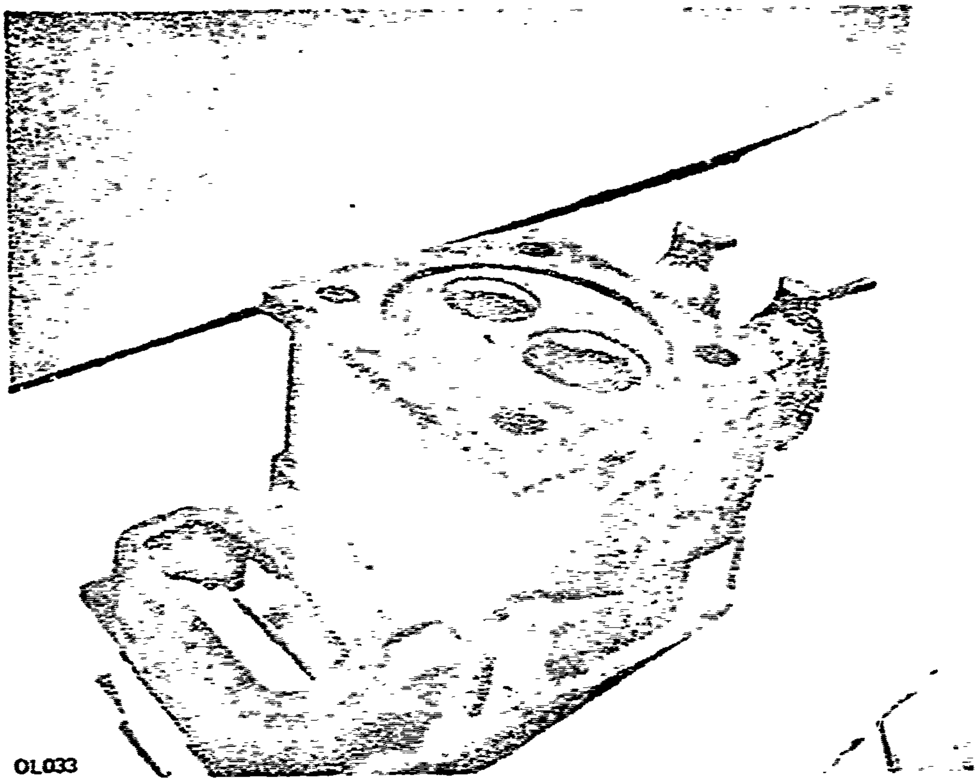
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Figure 4-21. Valve Seats

Rocker tappet surface wear was estimated as not more than 0.005 inch. Rocker bushing and rocker shaft wear were insignificant, indicating ample design margin and good lubrication.

Inspection of the fuel injector assembly disclosed only minor deposition of carbon on the nozzle tip (Figures 4-24 and 4-25). Pressure testing of the unit showed no visible leakage. Cracking and seating pressures were within acceptable limits. However, a discrepancy was noted in the spray pattern as shown in Figure 4-26. One of the 120° spaced orifices was completely blocked, one appeared nearly normal, and the third was greatly enlarged as shown at the right-hand side of Figure 4-26.

When the injector was re-installed in the cylinder head, the alignment of the enlarged orifice coincided with the previously described eroded head and piston areas. The assumption is that the erosion was caused by localized elevated temperatures and/or prolonged impingement of high velocity solid fuel.

Piston Assembly and Cylinder Barrel – Carbon buildup on the piston assembly was found to be relatively light (Figure 4-27). All rings were intact, and free in their respective grooves. Buildup in the oil control rings and associated return passageways was insufficient to impair their effectiveness. Maximum evidence of ring wear

Figure 4-22. Valve Condition, View 1

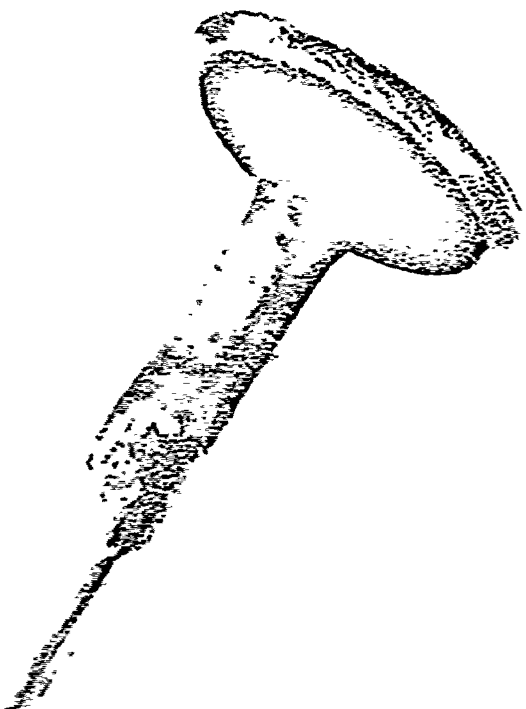

Figure 4-23. Valve Condition, View 2

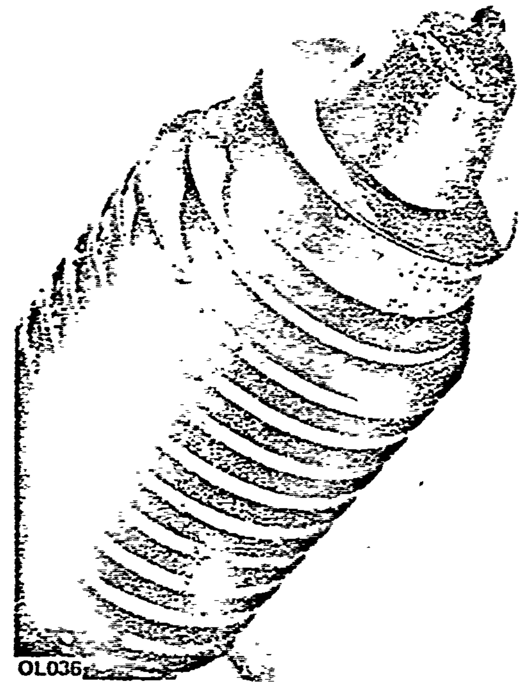

Figure 4-24. Injector Nozzle, View 1

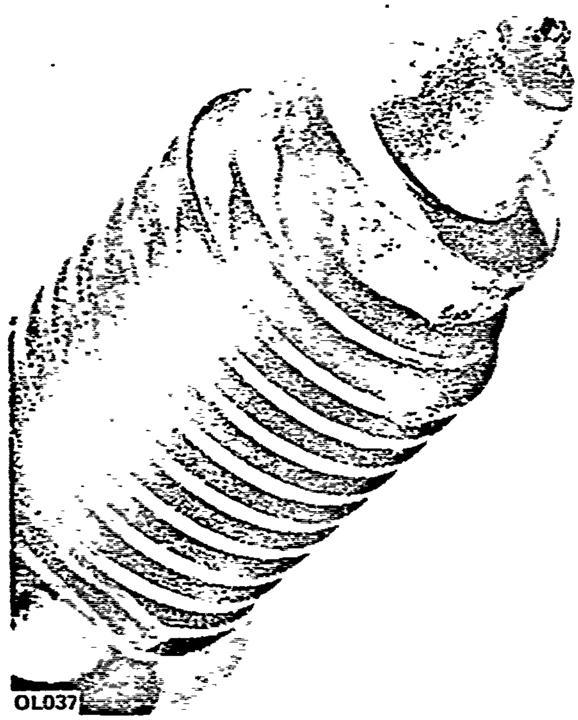

Figure 4-25. Injector Nozzle, View 2

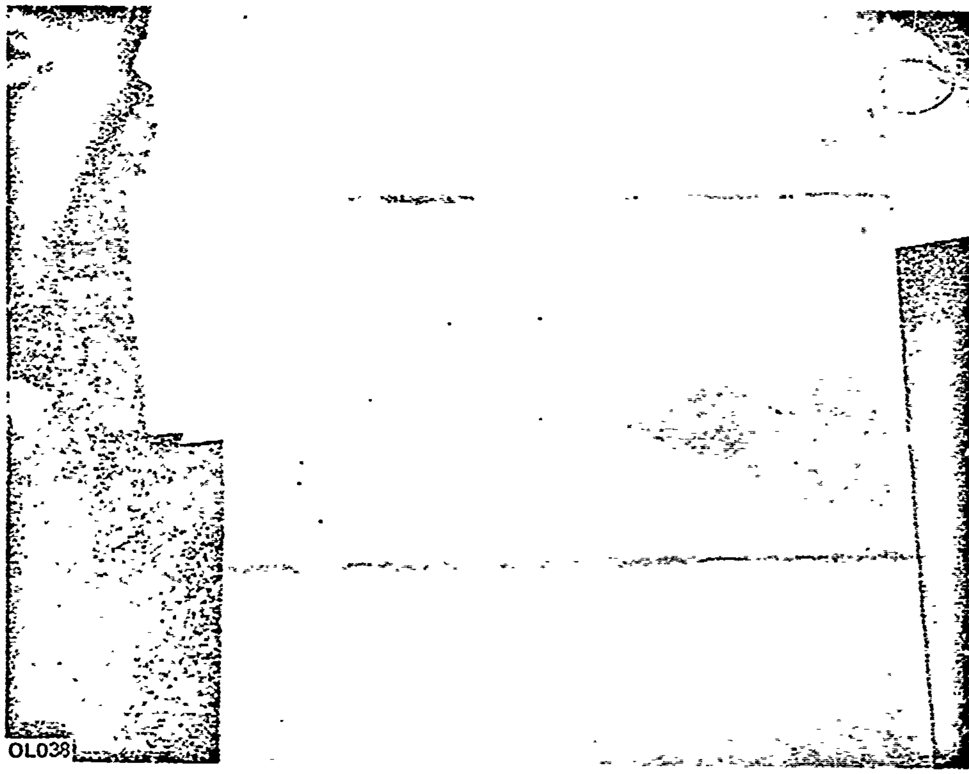

Figure 4-26. Spray Pattern

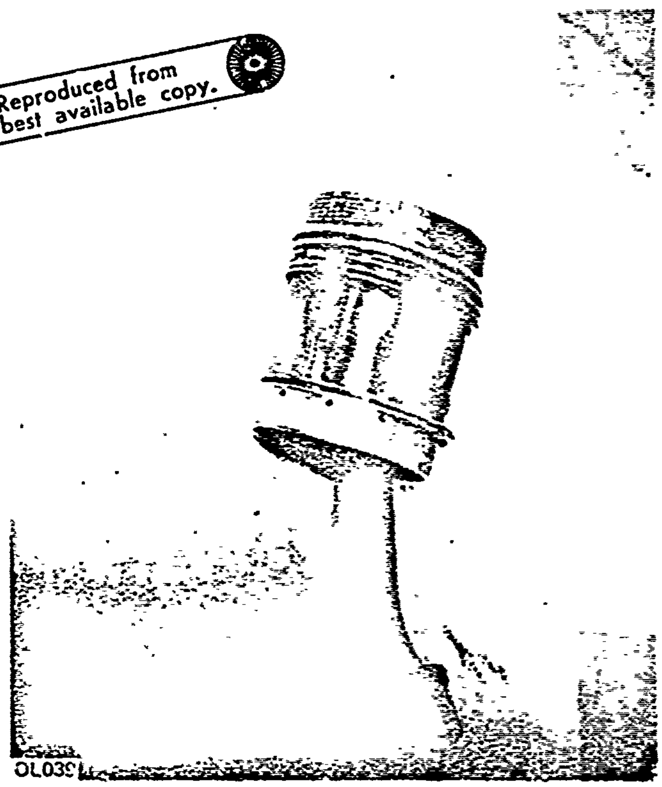

Figure 4-27. Piston Assembly

was exhibited by the wedge cross-sectioned firing ring (upper compression ring) which had developed an approximate 0.005-inch concave upper surface. Ring land wear associated with the firing ring and the second compression ring would normally preclude re-use of the piston without re-machining and installation of oversize rings. Maximum ring butt clearance encountered was 0.020 inch. Minimum clearance was 0.016 inch.

No evidence was found of excessive wrist pin clearance, or of the existence of connecting rod misalignment. Maximum piston thrust surface wear did not exceed 0.002 inch, and this occurred approximately one-half inch above the pin. Wear at the skirt was negligible.

Examination of the cylinder bore showed no significant ring ridge or evidence of scoring. Bore measurements taken parallel and normal to the wrist pin axis showed less than 0.001 inch taper or out-of-round.

Camshaft Assembly — Maximum measured camshaft journal wear did not exceed 0.0005 inch. There was no detectable bushing wear. Evidence of minor pitting existed on the trailing side of the exhaust lobe, but it was not possible to determine if the pitting resulted from service or an initial imperfection. Unusual lobe wear or scoring was not apparent. Although the oil pump cam follower was found to have an approximate 0.012 inch concave contact surface, the associated eccentricity exhibited no abnormality.

Examination of the gear train (cam and crank) showed negligible wear. Tooth mesh pattern showed an approximate 50% coverage with uniform distribution. Original hobbing marks were still visible in contact areas.

Crankshaft and Associated Bearings — Examination of crankshaft journal, thrust, and crankpin bearing surfaces disclosed no condition which would preclude the return of the unit to service. Maximum detectable wear (including out-of-round) did not exceed 0.0005 inch. However, there was a circumferential groove cut into the shaft in the area of the oil seal which could reduce the effectiveness and service life of a replacement seal. The groove was estimated to be 0.020-inch wide, and 0.015 to 0.020-inch deep. Seal examination showed no obvious cause. The assumption was that the condition resulted from a seal failure and/or subsequent replacement action which occurred relatively early in the test program.

Main bearing surfaces showed no evidence of unusual wear. Out-of-round did not exceed 0.0002 inch, and journal clearance was uniform at 0.003 inch to 0.0035 inch. Examination of the connecting rod bearing also showed no significant out-of-round or excessive clearance condition. Some discoloration of the bearing surface was noted, as shown in Figure 4-28. A number of bright spots which appeared to be minute imbedded flecks of foreign metallic substance were also observed. The source of this

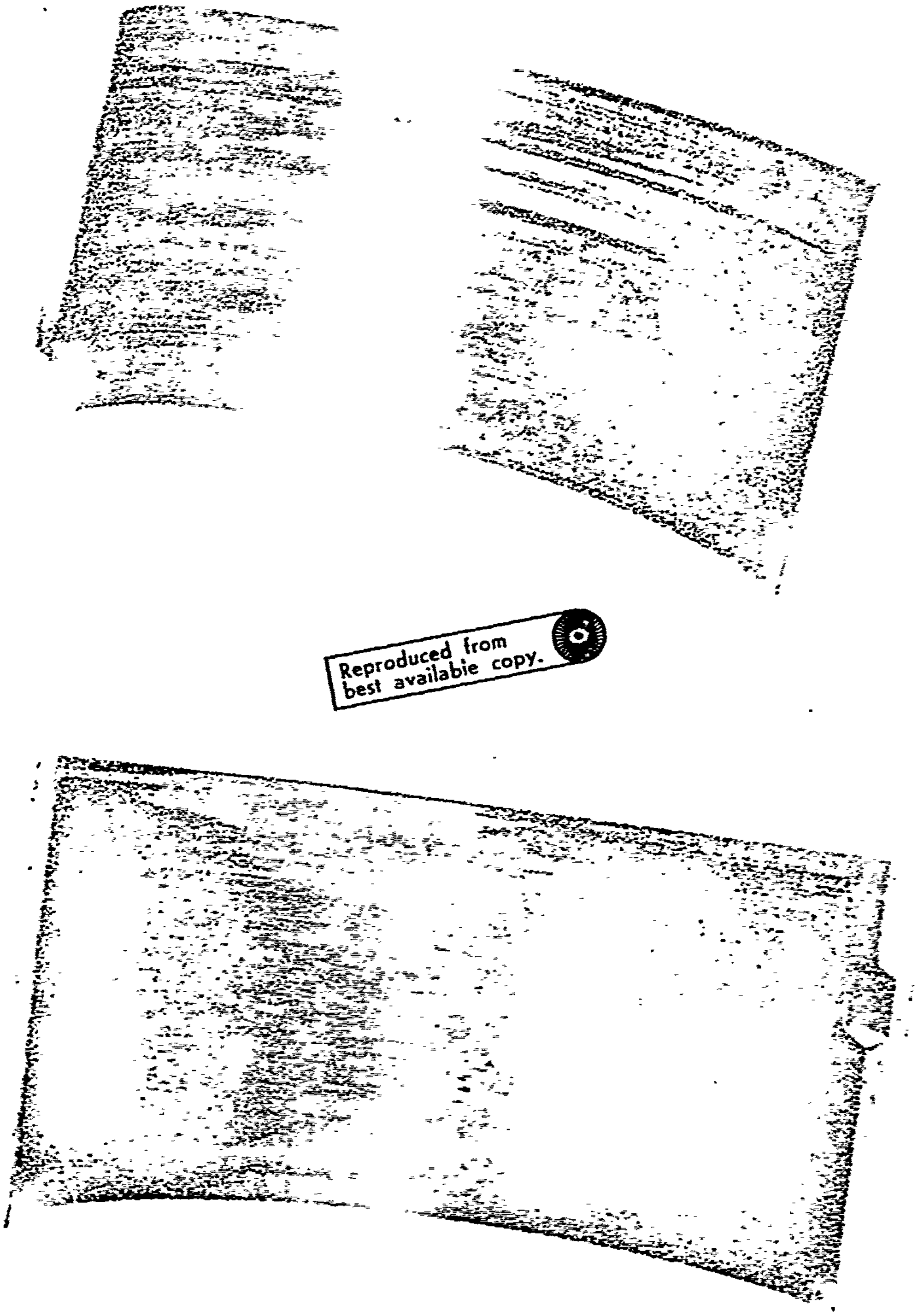

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Figure 4-28. Views of Connecting Rod Bearing

material was not found, and since a similar condition did not appear on the main bearing surfaces, the assumption was that the abnormality was restricted to the particular set of rod inserts as opposed to evidence of an oilborne contaminant.

Crankshaft end clearance was found to be excessive (0.016+ inch). Subsequent examination of the horse-shoe thrust washers at the gear-case end showed 0.008-inch wear. The washers at the flywheel end showed no evidence of contact with the crankshaft thrust face. The condition is believed to have resulted from either alternator magnetic-field-induced thrust forces, or alternator end bearing preloading.

Governor Assembly — Examination of the governor assembly disclosed no condition which would warrant overall replacement. Minor flyweight hinge-pin wear was noted in the area of pin engagement in the flyweight carrier. The wear was not considered sufficient to introduce instability. However, in view of the low replacement cost, re-use of the pins was not recommended.

Oil Pump Assembly — There was no evidence of unusual oil pump wear. The pump was capable of maintaining a system pressure of 35 psi at 1800 rpm at the termination of the 24,577-hr test run.

Fuel Injection Pump — Examination of the injection pump disclosed no abnormal wear. Metering was found to be good, and the unit was capable of maintaining normal pressure at engine full-load fuel-volume demand.

Summation — Considering the period of operation, the engine generator unit was found to be in remarkably good overall condition at the end of the test. The conclusion was that the unit could be returned to service with a good life expectancy after accomplishing the following overhaul tasks:

a. Replace valve guides.

b. Re-surface valve seats.

c. Install new valves.

d. Re-grind rocker tappet surfaces.

e. Install new oil pump cam follower.

f. Re-surface valve cam followers.

g. Fit new piston, ring set, wrist pin, and bushing.

h. Metal-spray or hard-chrome-plate the crankshaft oil seal area to fill groove, and re-grind to standard size.

i. Replace the oil seal.

j. Install new connecting rod bearing set.

k. Install new crankshaft thrust washer set.

l. Install new injector pump assembly.

m. Install new injector assembly.

n. Correct crankshaft thrust preloading.

o. Repair crack in cooling air exhaust plenum.

p. Install new camshaft extension seal.

4.3.2 ENGINE GENERATOR NO. 2

4.3.2.1 REPORT NO. 1

Date:	29 June 1970
Engine Generator Unit:	No. 2
Hour Meter Reading:	576 hours

Observations — Engine generator ceased to operate at 576 hours (approximately 476 hours into the first exercise cycle).

Cause — Investigation and inspection subsequent to stoppage showed that the fuel injector was heavily covered with carbon deposits, thus preventing fuel from entering the combustion chamber.

Corrective Action — Faulty injector was removed and replaced with a new unit and test continued. The faulty injector was returned to the vendor for failure analysis. Disassembly of the injector indicated that the injector valve had failed and caused improper metering of the fuel to the combustion chamber. The opinion of the investigator was that the injection valve failure could have been caused by the presence of water in the fuel supply. An investigation of the fuel supply revealed no visible water.

4.3.2.2 REPORT NO. 2, INSPECTION

Date:	9 March 1971
Engine Generator Unit:	No. 2
Engine Hours:	5370
Hours on Injector:	4794

Note

This engine was stopped and inspected during modification of the generator to external voltage control.

Inspection Items Accomplished:

a. Changed fuel filter element.

b. Changed lube oil filter element.

c. Washed air cleaner screen.

d. Replaced fuel injector with new unit.

e. Took oil sample.

f. Made general inspection for leaks, tightness of bolts, etc.

Comments on Items — There were no failures, loose bolts, leaks, or other malfunctions noted on this unit. Filters all appeared to be clean.

4.3.2.3 REPORT NO. 3, DISASSEMBLY AND INSPECTION

Date:	11 January 1972
Engine Generator Unit:	No. 2
Engine Hours:	6732
No. of Exercise Cycles:	1079

The test program on this unit commenced in June of 1970, and was terminated in January of 1972. The unit completed a 2-year series of cold start tests, long-term exercise tests, and accelerated exercise tests. All tests were accomplished with a relatively light fixed load (1 kW). The engine was disassembled, inspected, and rebuilt. Disassembly was witnessed by representatives from U.S. Coast Guard Headquarters and General Dynamics. The unit was rebuilt to "as new condition" prior to being shipped to the Coast Guard for subsequent use.

General Condition:

a. Exterior of engine generator was clean and showed no evidence of fuel or oil leaks.

b. Interior surfaces of the cooling ducting, cooling fins, and plenum were clean and free from carbon/dirt accumulation.

c. The interior of the combustion exhaust piping was free of carbon buildup, other than for a deposited layer of 0.03 inch measured at the 45° elbow in the collector plenum.

d. No evidence of corrosion was found on either the engine or generator.

Cylinder and Piston Assembly:

a. Cylinder wear was measured and found to be 0.0015 inch (manufacturer's allowable is 0.010 inch). The cylinder was lightly honed prior to reassembly to break the cylinder wall glaze.

b. The piston had less than 0.001-inch wear on the skirt.

c. The wrist pin showed no wear.

d. The cylinder head showed a light deposit of carbon in the combustion area, and this was wire-brush cleaned prior to reassembly.

Valves:

a. Both intake and exhaust valves showed wear on the faces. Consequently, they were replaced with new valves.

b. Valve seats showed no wear, distortion, or cutting.

c. The valve guides showed no measurable wear.

Bearings:

a. The connecting rod bearing showed 0.002-inch wear, and was replaced with a new bearing.

b. The crankshaft had less than 0.001-inch wear on the journals, and was re-installed in the engine.

c. Crankshaft main bearings showed little wear and were not replaced.

d. The camshaft and bushings showed no visible wear and were not replaced.

Fuel Injector System:

a. The fuel injector was removed, tested, and photographed. The pressure test showed a normal spray pattern despite the carbon buildup around each of the nozzle holes (see Figure 4-29). The injector was replaced with a new unit.

b. The high pressure fuel pump was replaced as a routine measure. Although no indication of any malfunction in the original unit was present, there is no positive way to evaluate wear of the fuel lift pump diaphragm. Therefore, the entire unit was replaced.

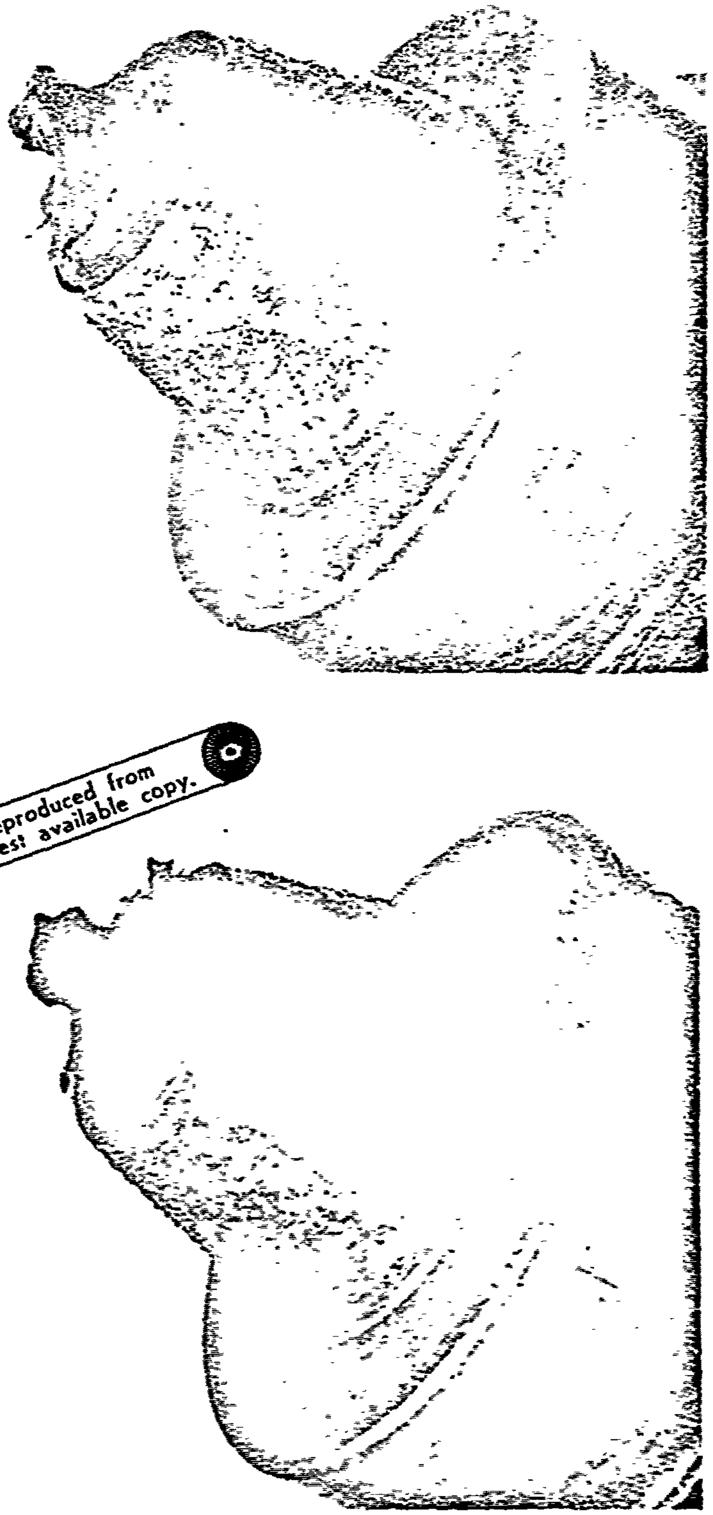

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Figure 4-29. Views of Injector Following Engine No. 2 Disassembly

Lubrication System:

a. The lubrication pump suction valve was replaced because the original valve was damaged during disassembly. There was no indication of wear in the lube oil pump.

b. All oil lines and fittings were inspected for damage and reassembled on the unit.

c. The lube oil tank was steam cleaned and then flushed with lube oil.

Engine Governor:

a. The governor pins and carrier plate were replaced as both showed wear at the contact points.

Generator:

a. The generator was disassembled and the end bearing was found to be loose in the end bell. Rather than rework the end bell of a used unit, the entire generator was replaced with a new unit.

b. The original nonstandard electrical harness was replaced with a new harness.

Miscellaneous:

a. The engine was reassembled with new seals, gaskets, joints, and filters.

b. The engine generator and frame were cleaned and painted after reassembly.

c. The unit was operated for 7 hours with a load of 22 amps. No leaks were detected from any fittings or joints.

4.4 OTHER COMMENTS AND OBSERVATIONS

4.4.1 VIBRATION ISOLATION BASE

The LNB engine generators are mounted on a vibration-isolation type base. This Fra-Bol (trade name) base is cushioned from the exterior frame by four double Korfund (trade name) elastomer pads mounted in 30° inclined channel sections. The upper Korfund pads are rated at 500 lbs per 1/4-inch deflection, and the lower pads are rated at 300 lbs per 1/4-inch deflection. Compression on the pads can be adjusted by changing the tension on four mounting bolts. During nearly 3 years of test, no maintenance or adjustment of the mounting base was required. Further, there was no indication of any deterioration of the Korfund pads during this time.

4.4.2 FUEL SYSTEM

Tank and Filters — The fuel supply tank used during the test program was configured to represent one of the four LNB tanks (1100-gallons capacity) as nearly as practicable. The tank was constructed with the same dimensions and was purged with dry nitrogen. The tank interior was coated with white epoxy finish as in the LNB configuration, and two stages of fuel filtration consisted of a water separator/filter in the fuel supply line and another filter mounted on the engine. The element in the second filter was replaced at 13,001 hours on Engine Generator No. 1, and at 5370 hours on Engine Generator No. 2.

During the operational inspections, no water was ever detected in the separator/filter unit. The paper element removed from the second unit on Engine Generator No. 1 at 13,001 hours showed no evidence of contamination, nor did the element removed from Engine Generator No. 2 at 5370 hours show any evidence of contamination. Diesel fuel used throughout the test program was commercial-grade No. 2 Diesel Oil, and no special procedures were specified during refueling other than ordinary cleanliness to ensure against contamination of the tank from dirt.

Fuel Lift Pump — A diaphragm-type fuel lift pump was installed on each engine. This pump was required to boost the fuel through the filters and plumbing to the high-pressure injector pump. During nearly 3 years of testing, no failures or malfunctions occurred on these pumps. Also, there have been no reports of lift-pump failures during field operations. Should a failure occur, it would most likely be a rupture of the diaphragm, which might allow fuel oil to enter the crankcase and be mixed with the lubricating oil. It is interesting to note in this regard, that the manufacturer claims the engine is capable (should such a situation occur in the extreme) of operating with almost pure fuel oil in the crankcase.

Fuel Injector Pump and Governor — The fuel-injector pump and engine-speed governor are internally mounted within the engine case. During testing, no failures or malfunctions occurred with these units.

Fuel Injectors — The fuel injector used on LNB diesel engines, and also on the test engines, is a multi-hole nozzle type. During the test program, a number of injector changes were made, as tabulated below:

Engine	Injector Replaced (Date)	Hours On Injector	Remarks
No. 1	10/13/70	9,511	Nozzle blocked with carbon.
No. 1	3/8/71	3,490	Routine replacement for start of new test.

Engine	Injector Replaced (Date)	Hours On Injector	Remarks
No. 1	6/29/72	11,556	Partial failure caused by blockage of one of the three nozzle holes. Engine continued operation to end of test at reduced load.
No. 2	6/29/70	576	Injector not operating properly – failure of injector valve.
No. 2	3/9/71	4,938	Routine replacement for start of new test.
No. 2	--	1,318	Injector operating normally when test was terminated on 1/6/72.

Photographs of injector nozzles, obtained during the test program, appear earlier in this section. From the above tabulation, the average life expectancy for injector units is estimated to be in the vicinity of 8000 hours. This expectancy is more than adequate when compared with the planned replacement schedule of 6 months (4400 hours).

4.4.3 LUBRICATING SYSTEM

The dry sump lubricating system developed for the LNB application experienced no failures or malfunctions since finalization of the plumbing configuration (refer to paragraph 4.3.1.1 for description of an early failure). Use of a large reservoir has assured an adequate supply of oil for long periods of unattended operation. Oil consumption averaged 0.26 pint per day on Engine No. 1, and the quality of the oil did not deteriorate significantly after long use (over 10,000 hours). There have been no failures in the modified lube oil pump or its associated plumbing.

The lube oil filter element was removed from Engine No. 1 at 13,001 hours and at 24,557 hours. They were relatively uncontaminated, with no evidence of sludge formation. Early problems with the injector plumbing had caused slight dilution of the oil on Engine No. 1, but the volume change due to fuel oil dilution was not measurable in the lube oil reservoir.

Lubricating Oil — The lubricating oil used for all diesel engine testing at General Dynamics was Shell Rotella 20W/40. This oil is one of several recommended by the engine manufacturer. At the start of each test, the lube oil reservoir was filled to the 22 gallon level. Periodic oil samples were taken during the tests for spectrographic analysis. Summaries of the analyses are given in Tables 4-4 and 4-5.

Table 4-4. Lube Oil Analysis for Engine No. 1

Date Anal.	Engine Hours	SUS Vis @130°F.	Moisture	°F. Flash Pt.	Fuel Dilu.	SAE#	Anti Frze.	Quantometer Readings (Parts per Million) Lead	Iron	Alum.	Copr.	Chrom.	Tin	Silc. (Dirt)
1/5/70	2,200	169	Neg.	370	Pos.	20	Neg.	0	6	4	36	0	0	2
1/14/70	3,000	170	Neg.	380	Trace	20	Neg.	0	12	6	40	4	8	8
3/6/70	4,000	164	Neg.	410	Neg.	20	Neg.	0	10	8	43	4	0	2
4/6/70	5,000	172	Neg.	280	Pos.	20	Neg.	30	8	6	32	4	0	6
4/27/70	5,500	167	Neg.	320	Pos.	20	Neg.	0	8	2	34	0	0	2
5/19/70	6,000	125	Neg.	240	Pos.	20	Neg.	0	12	0	54	0	0	0
6/1/70	6,500	140	Neg.	200	15%	20	Neg.	0	24	0	26	0	2	0
6/23/70	6,871	131	Neg.	200	Pos.	20	Neg.	0	14	6	30	2	0	8
6/23/70	OIL PARTIALLY REPLACED (12 GALS. SHELL ROTELLA 20W/40)													
6/30/70	7,031	238	Neg.	300	Pos.	30	Neg.	0	0	3	9	2	0	1
7/29/70	7,517	223	Neg.	400	Neg.	30	Neg.	0	0	4	9	0	4	4
8/11/70	8,000	192	Neg.	340	Pos.	30	Neg.	0	0	1	3	0	0	13
10/9/70	9,420	135	Neg.	250	Pos.	20	Neg.	0	8	4	12	2	2	4
10/13/70	9,511	OIL REPLACED WITH 22 GALS. SHELL ROTELLA 20W/40												
11/3/70	10,000	173	Neg.	300	Neg.	20	Neg.	0	6	10	18	10	4	2
11/24/70	10,503	141	Neg.	340	Pos.	20	Neg.	0	3	0	5	0	4	10
12/15/70	11,000	140	Neg.	210	Pos.	20	Neg.	0	2	10	16	10	0	4
1/6/71	11,500	182	Neg.	380	Trace	20	Neg.	0	5	0	3	0	4	10
1/26/71	12,000	154	Neg.	350	Pos.	30	Neg.	0	5	0	10	0	4	10
2/19/71	12,515	149	Neg.	320	Pos.	20	Neg.	0	6	0	9	0	2	10
3/12/71	13,001	129	Neg.	340	Pos.	20	Neg.	0	6	0	6	0	1	11
4/14/71	14,422	-	MISSING	-	-	-	-	-	-	-	-	-	-	-
8/19/71	16,560	188	Neg.	290	Pos.	30	Neg.	-	16	1	12	0	3	12
8/30/71	17,020	191	Neg.	300	Pos.	30	Neg.	-	16	4	6	0	1	10

Table 4-4. Lube Oil Analysis for Engine No. 1 (Continued)

Date Anal.	Engine Hours	SUS Vis @130°F.	Moisture	°F. Flash Pt.	Fuel Dilu.	SAE#	Anti-Frze.		Quantometer Readings (Parts per Million) Lead	Iron	Alum.	Copr.	Chrom.	Tin	Silc. (Dirt)
10/20/71	18,000	———	MISSING	———	———	———	Neg.		-	17	3	10	0	2	11
12/6/71	10,200	220	Neg.	380	Trace	30	Neg.		.	22	2	12	0	0	10
1/5/72	20,075	(OIL REPLACED WITH 22 GALLONS SHELL ROTELLA 20W/40)													
1/5/72	20,075	———	MISSING	———	———	———	Neg.			25	6	16	2	3	16

Table 4-5. Lube Oil Analysis for Engine No. 2

Date Anal.	Engine Hours	SUS Vis @130°F.	Moisture	°F. Flash Pt.	Fuel Dilu.	SAE#	Anti-Frze.		Quantometer Readings (Parts per Million) Lead	Iron	Alum.	Copr.	Chrom.	Tin	Silc. (Dirt)
6/17/70	300		MISSING				Neg.		0	0	0	1	4	1	0
6/30/70	500	211	Neg.	420	Neg.	30	Neg.		0	6	2	2	0	2	2
7/21/70	995	220	Neg.	390	Pos.	30	Neg.		50	11	9	5	5	7	3
8/11/70	1,469	203	Neg.	390	Pos.	20	Neg.		0	1	0	1	0	0	11
10/9/70	2,157		MISSING				Neg.		0	8	8	8	8	0	12
11/20/70	3,097	222	Neg.	355	Pos.	30	Neg.		0	16	0	1	0	2	11
12/10/70	3,869	181	Neg.	390	Pos.	20	Neg.		0	1	0	1	0	8	10
1/6/71	4,522	150	Neg.	200	Pos.	20	Neg.		0	6	0	9	0	4	10
2/11/71	4,767	181	Neg.	370	Pos.	20	Neg.		0	13	2	13	0	2	15
3/1/71	5,201	183	Neg.	360	Pos.	20	Neg.		0	5	0	6	0	6	10
3/9/71	5,370	180	Neg.	320	Pos.	20	Neg.		0	6	0	2	0	1	14
8/25/71	5,749	182	Neg.	390	Trace	20	Neg.		-	17	0	3	0	3	10
1/5/72	6,681		MISSING				Neg.		-	15	3	10	1	3	14

From Table 4-4, it can be seen that fuel dilution affected viscosity and flash-point characteristics of the lube oil between 2200 and 6871 hours. The dilution had occurred prior to 1000 hours (during initial testing), and resulted from improperly tightened fittings on the fuel leak-off line (return line). The dilution was not considered detrimental to engine operation until the flash point of the fuel was reduced to 200°F. The lube oil was partially replaced at 6871 hours, while the test continued. Approximately 12 gallons were replaced with new oil at this time. The subsequent viscosity and flash-point measurements showed an improvement to 238 SUS and 360°F, respectively. At 9511 hours (during shutdown for injector replacement) the lube oil reservoi[illegible] [illegible]as completely drained and 22 gallons of new oil were added. A corresponding increase in viscosity and flash point was then indicated in the 10,000-hour oil sample.

It should be noted also that a complete change of lube oil is normally made on the operational LNB at 6 months (4400 hours) at the same time that the fuel and oil filters, and injector, are replaced. Again, the test results showed that the lube oil supply was adequate, with considerable reserve.

4.4.4 VALIDATION OF OPERATION AND MAINTENANCE RECOMMENDATIONS

During the period of the tests described herein, production LNB's were being delivered and deployed. Their operation and maintenance procedures were, and are, being accomplished in accordance with instruction manuals prepared on the basis of early power plant test results and, of course, on the basis of the performance similar installations of the engine and generator had previously d[illegible]strated. The procedures, very briefly, call for service every 3 months; with oil, f[illegible] [illegible]nd injector changes at 6 months, and engine overhaul after 2 years of operation. [illegible] [illegible]an be seen from the results obtained with the test engines, this maintenance schedule may be conservative, yet it is consistent with the degree of reliability desired for the LNB. Also based on the test results, it may be possible to extend the maintenance period to 6 months while retaining a high level of reliability. However, because the tests as reported were limited to two engines (whereas seven LNB's are presently operational) it would appear prudent to place principal emphasis on the performance record of the deployed LNB in actual operational situations, including maintenance by service personnel. In that context, the results of the test program should be considered as conclusive validation of the suitability of the engine/generator system for the LNB mission, and as an indicator of possible savings in service costs (via extension of the service intervals) as on-station operational and maintenance experience is accumulated.

5. CONCLUSIONS

Based on three years of power plant testing, as reported, it is concluded that:

- The diesel engine generators as modified for the LNB mission are highly reliable power sources, capable of long-term unattended operations at the loads of the LNB, and will perform in excess of two years before overhaul is required of the engines and generators.
- The present 3-month service interval can probably be extended, with 6 months being a distinct possibility. Recognizing that the test program was limited to two units however, it is recommended that plans for increasing the service interval be based primarily on experience accumulated aboard operational LNB. Unscheduled maintenance, between regular service visits, should be minimal.
- The standby engine can be counted on to start reliably over a range of temperatures including the lowest temperature expected (30°F) in the engine compartment.
- The engine-generator unit is capable of operating for prolonged periods under a variety of loading conditions ranging from 30% to 85% of rated output.
- An injector life of more than 8000 hours (one continuous year) is indicated.
- The 25-gallon oil tank is capable of sustaining engine operations for an equal period: one year.
- The engine-generator unit is satisfactory for all operational requirements of the LNB in its present configuration, and is very probably capable of operating at significantly higher average loads should future mission requirements call for additional power.